ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

TABLE OF CONTENTS

List of Tables and Figures

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

I. EXECUTIVE SUMMARY

Over the past 20 years, considerable progress has been made in the control and management of point and nonpoint sources of contaminants. Reduced loadings of contaminants have, in general, resulted in a 50-70% reduction of contaminant levels in fish between the early 1970s and the mid 1980s (Environment Canada and U.S. Environmental Protection Agency 1995; 1997). However, since the mid 1980s, ambient levels of contaminants appear to have generally either leveled off or their rate of decrease has slowed substantially. Health advisories on certain fishes remain in effect in all of the Great Lakes. It is believed that the major reason why contaminant levels in fish have generally leveled off and health advisories on human consumption of fish remain in effect is that there are continued inputs of contaminants from the atmosphere, land runoff, and contaminated sediment. As a result, the lakes are now a source of contaminants to the atmosphere, which in turn, deposits contaminants back into the lakes (Environment Canada and U.S. Environmental Protection Agency 1995; 1997).

The importance of the contaminated sediment issue continues to rise in both the United States and Canada. For example, the U.S. Environmental Protection Agency's (EPA) Region V has identified cleaning up contaminated sediment as one of its top six priorities in its Agenda for Action for fiscal year 1997 (U. S. Environmental Protection Agency 1997), and as one of its top five priorities in its Agenda for Action for fiscal years 1998 and 1999 (U. S. Environmental Protection Agency 1998a; 1999). The Agenda for Action states that:

> *Polluted sediments are the largest major source of contaminants to the Great Lakes food chain, and over 97% (8,325 km) of the shoreline is considered impaired. The Region V sediment inventory contains 346 contaminated sediment sites. Fish consumption advisories remain in place throughout the Great Lakes and many inland lakes. Contaminated sediments also cause restriction and delays in the dredging of navigable waterways, which in turn can negatively affect local and regional economies. Contaminated sediments must be cleaned up before they move downstream or into open waters, which makes them inaccessible and cleanup impossible.*

Contaminated sediment has been identified as a source of ecological impacts throughout the Great Lakes Basin. All 42 Areas of Concern in the Great Lakes Basin have contaminated sediment based on the application of chemical guidelines. While contaminated sediment is not designated as a specific impairment in Annex 2 of the Great Lakes Water Quality Agreement (GLWQA), in-place pollutants potentially pose a challenge to restoring 11 of the 14 beneficial use impairments: restrictions on fish and wildlife consumption;

degradation of fish and wildlife populations; fish tumors or other deformities; bird or animal deformities or reproductive problems; degradation of benthos; loss of fish and wildlife habitat; eutrophication or undesirable algae; degradation of phytoplankton or zooplankton populations; degradation of aesthetics; added costs to agriculture or industry; and restrictions on dredging activities.

The 14 beneficial uses identified in the GLWQA can be grouped into four aspects of ecosystem health or state: human health, societal value, economic value, and ecological performance. The first eight of the eleven beneficial use impairments identified above have to do with ecological performance. Therefore, restoration of their use and the realization of ecological benefit requires an understanding of the relationship between contaminated sediment and the specific use impairment. It is also imperative, prior to embarking upon sediment remediation, to have developed some quantifiable expectation of result (ecological benefit) and a program to follow the predicted recovery.

In most Areas of Concern, the documentation of the sediment problem has not been quantitatively coupled to the ecological beneficial use impairments. Therefore, stipulating how much needs to be cleaned up, why, and what improvements can be expected to the beneficial use impairment(s) over time has not been possible. A clear understanding of these relationships and some level of quantification is critical for the development of a complete sediment management strategy. This understanding should provide adequate justification for an active cleanup program, and also represents a principle consideration in the adoption of non-intervention alternative strategies. In developing this understanding, it is important not only to know the existing degree of ecological impairment associated with sediment contaminants, but also the circumstances under which those relationships and impacts might change (i.e., contaminants become more available or more detrimental).

Over the past thirteen years, over $580 million has been spent on 38 remediation projects in 19 Areas of Concern. Of these sediment remediation projects, only two currently have adequate data and information on ecological effectiveness (i.e., post-project monitoring of beneficial use restoration). In some cases there is planned monitoring of ecological effectiveness, but the data will not be available for a number of years. In the cases where sediment remediation was undertaken as a result of regulatory action, the projects were designed to remove a mass of contaminants to reduce environmental risk. These projects were very effective in meeting the regulatory requirements, and indeed are consistent with the step-wise and incremental approach to management of contaminated sediment called for by the Great Lakes Water Quality Board (WQB).

However, it is recognized that in many cases, much more effort should be placed on forecasting and assessing ecological recovery of an Area of Concern, as well as beneficial use restoration consistent with Annex 2 of the GLWQA. Therefore, SedPAC recommends:

- **that much greater emphasis be placed on post-project monitoring of effectiveness of sediment remediation (i.e., assessment of effectiveness relative to restoration of uses, with appropriate quality assurance/quality control).**

One way of achieving this would be for the State/Provincial/Federal agency staff responsible for sediment remediation to incorporate into settlements and cooperative agreements some specific commitments and resources required for post-project monitoring of effectiveness of sediment remediation. Good examples of this include the Welland River project (Ontario), the settlement under the Natural Resource Damage Assessment for Saginaw River and Bay (Michigan), and the Thunder Bay cleanup project (Ontario).

Globally, the best documented ecological changes following sediment remediation are associated with actions relating to nutrient problems, generally in small lakes and ponds and in areas of low human population density, and usually the least costly remediations. Since affiliated research and monitoring have been so lacking, it has been difficult to evaluate the overall success of sediment remediation, in a general sense (i.e., to reasonably transfer lessons learned and recommendations on what things are still essential to know, and to achieve cost-effective and essential ecological remediation).

It is also recognized that ecological benefits of sediment remediation may not be seen because of the magnitude of the contaminated sediment problem in the area and in remaining downstream areas of contamination, which would mask or delay ecological recovery (e.g., Grand Calumet River/Indiana Harbor Ship Canal, Indiana). Areas of Concern where the probability of measuring ecological benefits of sediment remediation is high include: Manistique River, Michigan; Collingwood Harbour, Ontario; River Raisin, Michigan; Newburgh Lake Impoundment on the Rouge River, Michigan; and the unnamed tributary to the Ottawa River, Ohio. SedPAC recommends:

- **a high priority be placed on monitoring ecological benefits and beneficial use restoration at these sites.**

Although a basic understanding of aquatic ecosystem function and chemical fate is generally available, aquatic ecosystems appear to be sufficiently unique and our understanding sufficiently lacking. Therefore, an adaptive management approach is the prudent course to follow. This approach requires a much tighter coupling of research, monitoring, and management in every case to develop quantifiable, realistic goals and measures of success to achieve them.

Clearly, there are knowledge gaps in our understanding of the relationship between contaminated sediment and the 11 use impairments from the GLWQA that are potentially affected by contaminated sediment. Therefore, SedPAC recommends that:

- **additional research is essential to: quantify the relationships between contaminated sediment and known use impairments, forecast ecological benefits, and monitor ecological recovery and beneficial use restoration in a scientifically defensible and cost effective fashion.**

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

II. INTRODUCTION

Over the past 20 years, considerable progress has been made in the control and management of point and nonpoint sources of contaminants. Reduced loadings of contaminants have, in general, resulted in a 50-70% reduction of contaminant levels in fish between the early 1970s and the mid 1980s (Environment Canada and U.S. Environmental Protection Agency 1995; 1997). However, since the mid 1980s, ambient levels of contaminants appear to have generally either leveled off or their rate of decrease has slowed substantially. Health advisories on certain fishes remain in effect in all of the Great Lakes. It is believed that the major reason why contaminant levels in fish have generally leveled off and health advisories on human consumption of fish remain in effect is that there are continued inputs of contaminants from the atmosphere, land runoff, and contaminated sediment. As a result, the lakes are now a source of contaminants to the atmosphere, which in turn, deposits contaminants back into the lakes (Environment Canada and U.S. Environmental Protection Agency 1995; 1997).

The importance of the contaminated sediment issue continues to rise in both the United States and Canada. For example, U.S. EPA's Region V has identified cleaning up contaminated sediment as one of its top six priorities in its Agenda for Action for fiscal year 1997 (U. S. Environmental Protection Agency 1997), and as one of its top five priorities in its Agenda for Action for fiscal years 1998 and 1999 (U. S. Environmental Protection Agency 1998a; 1999). The Agenda for Action states that:

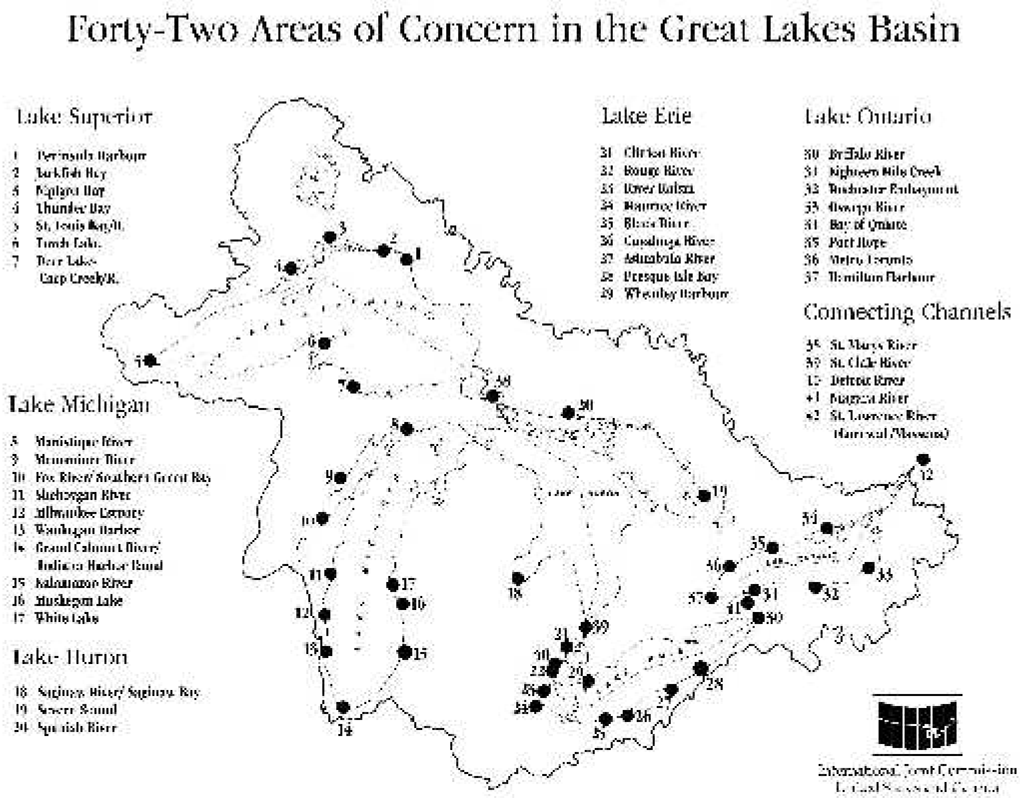
> *Polluted sediments are the largest major source of contaminants to the Great Lakes food chain, and over 97% (8,325 km) of the shoreline is considered impaired. The Region V sediment inventory contains 346 contaminated sediment sites. Fish consumption advisories remain in place throughout the Great Lakes and many inland lakes. Contaminated sediments also cause restriction and delays in the dredging of navigable waterways, which in turn can negatively affect local and regional economies. Contaminated sediments must be cleaned up before they move downstream or into open waters, which makes them inaccessible and cleanup impossible.*

Contaminated sediment has been identified as a source of ecological impacts throughout the Great Lakes Basin. All 42 Areas of Concern in the Great Lakes Basin have contaminated sediment based on the application of chemical guidelines (Figure 1). While contaminated sediment is not designated as a specific impairment in Annex 2 of the GLWQA, in-place pollutants potentially pose a challenge to restoring 11 of the 14 beneficial use impairments: restrictions on fish and wildlife consumption; degradation of fish and wildlife populations; fish tumors or other deformities; bird or animal deformities or reproductive problems;

degradation of benthos; loss of fish and wildlife habitat; eutrophication or undesirable algae; degradation of phytoplankton or zooplankton populations; degradation of aesthetics; added costs to agriculture or industry; and restrictions on dredging activities.

The 14 beneficial uses identified in the GLWQA can be grouped into four aspects of ecosystem "health" or state: human health, societal value, economic value, and ecological performance. The first eight of the eleven beneficial use impairments identified above have to do

Figure 1. Great Lakes Basin Areas of Concern



with ecological performance. Therefore, restoration of their use and the realization of ecological benefit requires an understanding of the relationship between contaminated sediment and the specific use impairment (Table 1). It is also imperative, prior to embarking upon sediment remediation, to have developed some quantifiable expectation of result (ecological benefit), and a program to follow the predicted recovery.

This interim report of SedPAC reviews the following: what is known about contaminated sediment, sediment contamination and remediation in the Great Lakes, measurements of ecological benefits, and also presents advice to managers and researchers on future evaluation of ecological effectiveness of sediment remediation.

Table 1. Ecological performance use impairments potentially associated with contaminated sediment and the number of Areas of Concern (AOCs) where these impairments have been found

USE IMPAIRMENT	NUMBER OF AOCs IMPAIRED (% OF 42 AOCs)
Restrictions on fish and wildlife consumption	36 (86%)
Degradation of fish and wildlife populations	30 (71%)
Fish tumors or other deformities	20 (48%)

Bird or animal deformities or reproduction problems	14 (33%)
Degradation of benthos	35 (83%)
Loss of fish and wildlife habitat	34 (81%)
Eutrophication or undesirable algae	21 (50%)
Degradation of phytoplankton or zooplankton populations	10 (24%)

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

III. CONTAMINATED SEDIMENT IN THE GREAT LAKES

In the late 1960s through the late 1970s, a series of comprehensive surveys of the geochemical composition of the surficial sediment in each of the Great Lakes were conducted. These surveys examined sediment samples from the top three centimeters, collected from a one or a ten square kilometer grid, to determine the spatial pattern of pelagic sediment. These data led Allan (1986) to conclude that there are two basic distribution patterns for trace metals in the pelagic zones of the Great Lakes. In addition, temporal changes in sediment quality were documented from sediment cores at selected stations (Zarull and Mudroch 1993).

The first grouping has its highest concentrations in the upper lakes, particularly Lake Superior and Georgian Bay, which is thought to be due to the bedrock composition of the Canadian Shield. This pattern of high concentration in the upper lakes occurs with most heavy metals associated with natural mineralization (e.g., chromium and nickel). These higher sediment concentrations may also result from the very low sedimentation rates and consequently low dilution of the upper lakes. Higher concentrations of chromium in some parts of Lakes Erie and Ontario have been attributed to the plating industries located in the lower lakes and connecting channels drainage basins (Thomas and Mudroch 1979; Allan 1986).

The other distribution pattern found in the open waters of the Great Lakes is associated with metals and organics originating from urban effluents. The greatest concentrations of these substances are found in the lower lakes, particularly in the vicinity of the western basin of Lake Erie, Lake St. Clair, and the Detroit River, along with the depositional basins of Lake Ontario (in particular, the Niagara basin). This pattern also holds for the distribution of lead, zinc, cadmium, and PCBs (Thomas and Mudroch 1979).

Analysis of contaminant concentrations from dated sediment cores indicates that the more recent concentrations of metals such as lead, copper, zinc, and mercury are considerably greater than their pre-industrial levels by up to a factor of ten. In general, the results showed that the loadings of inorganic contaminants had increased significantly since the 1900s and that organic contaminants began to accumulate in the sediment around the 1940s. The increase in these loadings to the Great Lakes sediment is ascribed to inputs from industry, agriculture, and municipalities along the shoreline, and to transport via tributaries. Atmospheric deposition has also contributed considerably to the sediment loadings of several contaminants (Kemp and Thomas 1976; Nriagu *et al.*1979; Thomas and Mudroch 1979; Durham and Oliver 1983; Nriagu 1986; Robbins *et al.* 1990).

The chronology of Lake Ontario sediment contamination by mirex and its subsequent redistribution illustrates the large-scale spatial and temporal changes that can be expected for a persistent organic contaminant. An investigation by Thomas and Frank (1987) indicated two sources of mirex to the lake. The Niagara River was the major source, which had resulted from loss during the manufacturing process; and the second source was from the Oswego River, which came from a spill to the river in the mid 1950s. Mirex from the Niagara River entered the lake and moved to the northwest, settling in the deep basin. A larger portion of the contaminated sediment was transported by a major circulation process and carried along the south shore. The size of the contaminated area of the surficial sediment continued to increase, even though production was discontinued in 1976. Changes in the distribution of mirex in the eastern basin are thought to have resulted from the transfer of sediment-bound mirex, since there was no additional source input in this area. The expanded distribution and increased concentrations that subsequently were observed between 1968 and 1977 could only be due to intermittent remobilization processes of Oswego River material. This phenomenon led to increased open lake contamination and far field contamination of the St. Lawrence River (Thomas and Frank 1987).

Another example of large-scale spatial and temporal changes in sediment contamination is the Saginaw River/Saginaw Bay, Lake Huron. Saginaw River is the major tributary to the Bay. During the 1960s, 1970s, and early 1980s, between 27 and 54 tonnes of PCBs were released from a General Motors Plant in Bay City, Michigan and found in and on the land adjacent to the Saginaw River (International Joint Commission 1987b). During 1986, a once-in-500 year flood occurred. This flood occurred in September 1986 and resulted from a rainfall of up to 30 cm over 36 hours in some areas of the watershed, followed by another 8-18 cm during the remaining 19 days of the month. This once-in-500 year flood resulted in considerable movement of PCB and other contaminated sediment throughout the watershed and Bay (Michigan Department of Natural Resources 1988).

The examples of mirex in Lake Ontario and PCBs in the Saginaw River/Bay demonstrate that local nearshore contamination is unstable and remobilization by physical, chemical, or biological processes will result in the transfer of an apparently local problem into lakewide contamination. Therefore, the time for positive action is when contaminated sediment is localized, since once the sediment disperses to the open lake, the resolution of the problem becomes very much more complex (Reynoldson *et al.* 1988).

Sediment contaminated with metals, persistent toxic organics, nutrients, and oxygen demanding substances can be found in many areas throughout the Great Lakes. However, the highest levels of sediment-associated contaminants and some of the worst manifestations of their resultant problems are found in the urban-industrial harbors, embayments, and river mouths. These are the areas that are likely the most significant, from an ecological point of view. These nearshore areas represent the spawning and nursery sites for most fish species, the nesting and feeding areas for most of the aquatic avian fauna, the areas of highest biological productivity, the areas of greatest human contact, and the primary places of direct human contact with the sediment.

All Areas of Concern contain some sediment with elevated levels of nutrients, metals, or persistent organic contaminants. Sediment data were gathered on different occasions over a number of years by a variety of investigators and were used not only to describe the extent of contamination, but also as the basis for "listing" a sediment problem in an Area of Concern. In these assessments, bulk chemical analyses were performed and the results were compared to dredging guidelines (International Joint Commission 1982). Early estimates of the potential costs of sediment cleanup, based on data such as these, provided a bleak economic picture for the Areas of Concern and the Great Lakes. Estimates by Leger (1989) for nine Areas of Concern - Southern Green Bay/Fox River, Milwaukee Harbor, Waukegan Harbor, Grand Calumet River/Indiana Harbor, Saginaw River/Bay, Clinton River, Rouge River, Black River, and Ashtabula River/Harbor - ranged from around $185 million to $604 million. In the Canadian Areas of Concern and the Ontario portion of the interconnecting channels, Wardlaw *et al.* (1995) estimated that the total volume of "highly" contaminated sediment was about 172,000 m^3. If it is assumed that all of the material will be dredged and placed in an existing confined disposal facility and we employ the cost estimate of \$25/yd^3 used by Leger (1989), the cost of cleanup can be estimated to be around \$4 million (\$25 x 157,276.8 yd^3). The term "highly" contaminated means having contaminant levels over Ontario's Severe Effects Level (Persaud *et al.* 1992). These preliminary cost estimates are highly sobering and show that contaminated sediment is a substantial challenge. However, these cost estimates have been so significant that benefits tend to be ignored, and the perception that prevails is one of cleanup activities being cost prohibitive.

Sediment cleanup in the Areas of Concern has been shrouded by the discussion of high costs. Also contributing to the perception that cleanup actions are not feasible is the lack of attention given to the potential to renew ecological well being. It is important to remember that there have been significant refinements to assessment approaches since dredging guidelines were derived. More recent approaches, while not specifically developed to quantify the contribution of sediment contaminants to beneficial use impairments, do have some ecological linkages. For example, Ontario's Provincial Sediment Quality Guidelines are biologically-based and literature derived chemical-by-chemical criteria (Persaud *et al.* 1992), and the U.S. EPA's chemically-based criteria are based on risk analysis (U.S. Environmental Protection Agency 1992).

A clear understanding of the ecological benefits to be accrued through sediment cleanup, and some level of quantification of those benefits, are critical for the development of a complete sediment management strategy. Documenting the sediment problem in this context will help stipulate how much needs to be cleaned up, why, and what improvements can be expected in the beneficial use impairments over time. This understanding can provide adequate justification for an active cleanup program, and also represents a principle consideration in the adoption of non- intervention alternative strategies. In developing this understanding, it is important not only to know the existing degree of ecological impairment associated with sediment contaminants, but also the circumstances under which those relationships and impacts might change (i.e., contaminants become more available or more detrimental).

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

IV. CONTAMINATED SEDIMENT AND THE AQUATIC ENVIRONMENT

In the Great Lakes, as in many aquatic systems, a considerable mass of persistent contaminants can be found in the bottom sediment. The accumulation of contaminants in the sediment at levels that are not rapidly lethal may result in long-term, subtle effects to the biota by direct uptake or through the foodweb. The cycling and bioavailability of sediment-associated contaminants in aquatic systems over both short and long time frames are controlled by physical, chemical, biological, and geological processes.

Physical processes affecting sediment contaminant distribution include mechanical disturbance at the sediment-water interface as a result of bioturbation, advection and diffusion, particle settling, resuspension, and burial. Some examples of significant geological processes affecting contaminant distribution and availability include weathering or mineral degradation, mineralization, leaching, and sedimentation. Chemical processes such as dissolution and precipitation, desorption, and oxidation and reduction can have profound effects, as well as biological processes such as decomposition, biochemical transformation, gas production and consumption, cell wall and membrane exchange/permeability, food web transfer, digestion, methylation, and pellet generation. In addition, the fundamental differences in physical, chemical, and biological properties and behavior of organic versus inorganic substances (metals, persistent organics, organo-metals, and nutrients) suggests the need for a more detailed knowledge of the area and the relative importance of these processes prior to completing an assessment of impact or planning remedial measures. Details of the major processes and their effects on contaminant cycling and movement can be found in Forstner and Whittman (1979), Salamons and Forstner (1984), Allan (1986), and Krezovich *et al.* (1987); however, it is important to explore the factors that affect bioavailability and uptake of contaminants, as well as the likely, quantifiable consequences of bioaccumulation.

The rate and mechanism of contaminant uptake from sediment by bottom-dwelling organisms can vary considerably among species, and even within species. Factors such as feeding ecology of the organisms, their developmental stage, season, behavior, and history of exposure affect contaminant uptake and body burdens. As well, different routes of uptake (soluble transfers versus contaminated food) can also be expected to affect tissue levels.

Experiments with organochlorine pesticides have yielded conflicting results on the relative significance of diet versus aqueous uptake. Within individual studies, available data on sediment- based bioconcentration factors for various organisms show a wide variation among species for a specific contaminant (Roesijadi *et al.* 1978a; 1978b). Accumulation of both organic and metal contaminants can be passive due to adsorption onto the organism, or it can be an active process driven through respiration. "Case-dwelling" species of benthic invertebrates have been thought less susceptible to contaminants than "free-living" organisms since the bioconcentration factors (BCF) have been found to be quite different for metals like copper and zinc. Similar differences have been found for oligochaete and amphipod tissue concentrations for PCBs and hexachlorobenzene.

Sediment type can profoundly influence the bioavailability of sediment-sorbed chemicals. Many researchers have reported an inverse relationship between chemical availability and sediment organic carbon content (Augenfield and Anderson 1982; Adams *et al.* 1983). There also appears to be a smaller, not as well defined relationship between sediment particle size and chemical availability. In fine-grained sediment, this is most likely due to the increased surface area available for adsorption and the reduced volume of interstitial water. Chemicals sorbed to suspensions of organic particles (both living, such as plankton, and non-living) may constitute sources of exposure for filter-feeding organisms and may be important in deposition. This pathway may be significant, as these organisms have been shown to accelerate the sedimentation processes by efficiently removing and depositing particles contained in the water column.

Several water quality conditions influence bioaccumulation of contaminants: temperature, pH, redox, water hardness, and physical disturbance. In addition, metals in mixtures may also compete for binding sites on organic molecules, resulting in antagonistic effects (e.g., cadmium and zinc, silver and copper).

The biological community itself can strongly influence the physical-chemical environment in the sediment, and in turn, affect the bioavailability of contaminants. For example: primary productivity influences the pH, which can influence metal chemistry; sulphate reduction by bacteria facilitates sulphide formation; the reduction of oxygen by organisms and their activities to anoxia affects redox conditions, and with it, metal redox conversion; the production of organic matter that may complex with contaminants; bioturbation influences sediment-water exchange processes and redox conditions; and methylation of some metals such as mercury.

Water based, BCFs indicate that benthic invertebrates generally accumulate to higher concentrations than do fish. This may be attributed to the greater degree of exposure of the benthic invertebrates at the sediment-water interface than fish. Biomagnification occurs when contaminant concentrations increase with successive steps in the trophic structure. However, well defined trophic levels may not exist in the aquatic ecosystem under examination, especially ones experiencing (or that have experienced) anthropogenically generated loadings of various contaminants. In addition, individual species may occupy more than one trophic level during the life cycle. These factors not only complicate process and exposure understanding, they also complicate monitoring program designs necessary to document improvement after remediation has taken place.

Metals, in their inorganic forms, do not appear to biomagnify appreciably in aquatic ecosystems; however, methylated forms of metals, like mercury, do biomagnify. Most persistent toxic organics demonstrate biomagnification to lesser or greater degrees; however, it appears that biomagnification is not as dramatic within aquatic food chains as terrestrial ones. Also, it appears that where the phenomenon does occur, the biomagnification factors between the lowest and highest trophic levels are usually less than one order of magnitude (U.S. Army Corps - Waterways Experiment Station 1984).

Ecological Effects of Contaminated Sediment

It was commonly assumed that chemicals sequestered within sediment were unavailable to biota, and therefore posed little threat to aquatic ecosystems. Although the laboratory and field studies are not overwhelming in number, both the risk and the impairment to organisms, including humans, have been conclusively established. Biota exposed to contaminated sediment may exhibit increased mortality, reduced growth and fecundity, or morphological anomalies. Studies have also shown that contaminated sediment can be responsible for mutagenic and other genotoxic impairments (Lower *et al*. 1985; West *et al*. 1986). These effects are not restricted to benthic organisms - plankton, fish, and humans are also affected both from direct contact and through the food chain.

Nuisance algal growth and nutrient relationships in lakes are well documented, with phosphorus being cited as the limiting nutrient. Some phosphorus is released during spring and fall lake circulation in dimictic lakes. In shallow, polymictic lakes, sedimentary phosphorus release may be more frequent, creating greater nuisance problems with the infusion of nutrients to overlying water, especially during summer recreational periods. This influx of nutrients usually results in abundant, undesirable phytoplankton growth, reducing water transparency, increasing color, and in severe cases, seriously depleting dissolved oxygen and potentially leading to fish kills. In addition, phytoplankton may be adversely impacted by contaminant-laden particulate matter.

Nau-Ritter and Wurster (1983) demonstrated that PCBs desorbed from chlorite and illite particles inhibited photosynthesis and reduced the chlorophyll - a content of natural phytoplankton assemblages. In a similar study, Powers *et al*. (1982) found that PCBs desorbed from particles caused reduced algal growth as well as reduced chlorophyll production. The time course for desorption and bioaccumulation appears to be quite rapid, with effects being documented within hours after exposure (Harding and Phillips 1978). The rapid transfer of PCBs and other xenobiotic chemicals from particulate material to phytoplankton has significant ramifications because it provides a mechanism for contaminants to be readily introduced to the base of the food web.

The detrimental effects of contaminated sediment on benthic and pelagic invertebrate organisms have been demonstrated in several laboratory studies. Prater and Anderson (1977a; 1977b), Hoke and Prater (1980), and Malueg *et al*. (1983) have shown that sediment taken from a variety of lentic and lotic ecosystems was lethal to invertebrates during short-term bioassays. Tagatz *et al*. (1985) exposed macrobenthic communities to sediment-bound and water-borne chlorinated organics, and found similar reductions in diversity to both exposures. Chapman and Fink (1984) measured the lethal and sublethal effects of contaminated whole sediment and sediment elutriates on the life cycle of a marine polychaete, and found that both sources were capable of producing abnormalities, mortalities, and reduced fecundities in larval and adult worms. The biotransformation of sediment-derived benzo[a]pyrene has been shown to result in the formation of potentially mutagenic and carcinogenic metabolites in depositional feeding amphipods (Reichert *et al*.1985). Other sublethal effects may be more subtle; for example, infaunal polychaetes, bivalves, and amphipods have been shown to exhibit impaired burrowing behavior when placed in pesticide-contaminated sediment (Gannon and Beeton 1971; Mohlenberg and Kiorboe 1983). Some observations have linked contaminants in sediment with alterations in genetic structure or aberrations in genetic expression. Warwick (1980) observed deformities in chironomid larvae mouthparts, which he attributed to contaminants. Wiederholm (1984) showed similar deformities in chironomid mouthparts ranging from occurrence rates of less than 1% at unpolluted sites (background) to 5-25% at highly polluted sites in Sweden. Milbrink (1983) has shown setal deformities in oligochaetes exposed to high sediment mercury levels.

Fish populations may also be impacted by chemicals derived from contaminated sediment. Laboratory studies have shown that fathead minnows held in the presence of contaminated natural sediment may suffer significant mortalities (Prater and Anderson 1977a, 1977b; Hoke and Prater 1980). Morphological anomalies have also been traced to contaminated sediment associations with fish. Malins *et al*. (1984) found consistent correlations between the occurrence of hepatic neoplasms in bottom-dwelling fish and concentrations of polynuclear aromatic hydrocarbons in sediment from Puget Sound, Washington. In addition, Harder *et al*. (1983) have demonstrated that sediment-degraded toxaphene was more toxic to the white mullet than to the non-degraded form. These studies illustrate the potential importance of sediment to the health and survival of pelagic and demersal fish species, but do not necessarily indicate a cause and effect relationship. While we can expect that fish will be exposed to chemicals that desorb from sediment and suspended particles, the relative contributions of these pathways to any observable biological effects are not obvious. Instead, laboratory bioassays and bioconcentration studies are often required as conclusive supporting evidence. The Elizabeth River, a subestuary of the Chesapeake Bay, is heavily contaminated with a variety of pollutants, particularly PAHs. The frequency and intensity of neoplasms, cataracts, enzyme induction, fin rot, and other lesions observed in fish populations have been correlated with the extent of sediment contamination. In addition, bioaccumulation of these same compounds in fish and resident crabs was also observed. However, essential laboratory studies were not conducted to establish contaminants in sediment as the cause of the observed impairments (U.S. Environmental Protection Agency 1998b).

There have been few examples of direct impacts of contaminated sediment on wildlife or humans. Bishop *et al*. (1995; 1999) found good correlations between a variety of chlorinated hydrocarbons in the sediment and concentrations in bird eggs. They felt this relationship indicated that the female contaminant body burden was obtained locally, just prior to egg laying. Other studies by Bishop *et al*. indicated a link between exposure of snapping turtle (*Chelydra s. serpentina)* eggs to contaminants (including sediment exposure) and developmental success (Bishop *et al.* 1991; 1998). Other investigations of environmentally occurring persistent organics have shown bioaccumulation and a range of effects in the mudpuppy (*Necturus maculosus*) (Bonin *et al*. 1995; Gendron *et al*. 1997). In the case of humans (*Homo sapiens*) there is only anecdotal evidence from cases like Monguagon Creek, a small tributary to the Detroit River, where incidental human contact with the sediment resulted in a skin rash. For the most part, assessments of sediment-associated contaminant impacts on the health of vertebrates (beyond fish) are inferential. This approach is known as risk assessment, and it involves hazard identification, toxicity assessment, exposure assessment, and risk characterization (National Academy of Sciences 1983).

Superfund risk assessments, which are aimed at evaluating and protecting human health, are designed to evaluate current and potential risks to the "reasonably maximally exposed individual" (U.S. Environmental Protection Agency 1989). Both cancer and non-cancer health effects for adults and children are evaluated. Data for the evaluation include concentrations of specific chemicals in the sediment, water column, and other media that are relevant to the potential exposure route. These routes of exposure may include: ingestion of contaminated water, inhalation of chemicals that volatilize, dermal contact, and fish consumption. The media-specific chemicals of potential concern are characterized based on their potential to cause either cancer or non-cancer health effects, or both. Once the "hazards" have been identified, the prescribed approach is continued to include toxicity evaluation, exposure assessment, and risk characterization. All of this leads to a potential remedial action, which itself follows a set of prescribed rules.

"Ecological risk assessment (ERA) is the estimation of the likelihood of undesired effects of human actions or natural events and the accompanying risks to nonhuman organisms, populations, and ecosystems" (Sutter 1997). The structure of ERA is based on human health risk assessment (HHRA), but it has been modified to accommodate differences between ecological systems and humans. "The principal one is that, unlike HHRA, which begins by identifying the hazard (e.g., the chemical is a carcinogen), ERA begins by dealing with the diversity of entities and responses that may be affected, of interactions and secondary effects that may occur, of scales at which effects may be considered, and of modes of exposure" (Sutter 1997). Risk characterization is by weight of evidence. Data from chemical analyses, toxicity tests, biological surveys, and biomarkers are employed to estimate the likelihood that significant effects are occurring, or will occur. The assessment requires that the nature, magnitude, and extent of effects on the designated assessment endpoints be depicted.

It is apparent that rarely is the relationship between a particular contaminant in the sediment and some observed ecological effect straightforward. Physical, chemical, and biological factors are interactive, antagonistic, and highly dynamic. These things often preclude a precise quantification of the degree of ecological impairment or effect attributable to a contaminant present in the sediment, and therefore, the degree of ecological improvement or benefit that can be achieved through remediation. Precision in quantifying impairment, remediation, and recovery is always improved through a better understanding of both the specifics of ecosystem functioning, as well as the behavior of the chemical(s) of concern in that particular ecosystem. Although a basic understanding of aquatic ecosystem function and chemical fate is generally available, it is also evident that systems appear to be sufficiently unique and our understanding sufficiently lacking. Therefore, an adaptive management approach is the prudent course to follow. This requires a much tighter coupling of research, monitoring, and management in every case to develop quantifiable, realistic goals and measures of success to achieve them.

Sediment Remediation and Ecological Improvements

Sediment removal has been used as a management technique in lakes as a means of deepening a lake to improve its recreational potential, to remove toxic substances from the system, to reduce nuisance aquatic macrophyte growth, and to prevent or reduce the internal nutrient cycling which may represent a significant fraction of the total nutrient loading (Larsen *et al.* 1975). Below are some examples of the removal of sediment contaminated by a nutrient (phosphorus), a metal (mercury), and a persistent toxic organic compound (PCBs) from lakes, rivers, and embayments outside the Great Lakes Basin.

<u>Nutrients</u>

Lake Trummen, Sweden, is one of the most thoroughly documented dredging projects in the world. An evaluation of the effectiveness of the dredging, whose main purpose was to reduce internal nutrient cycling and enrichment through sediment removal, took place over a twenty year plus time frame.

Lake Trummen, with a surface area of approximately 1 km^2, a drainage basin of some 12 km^2, and a mean depth of 2 m, was originally oligotrophic; however, it became hypertrophic after receiving both municipal and industrial discharges over a long period of time. In order to rectify the problems, both municipal and industrial waste effluents were curtailed in the late 1950s; however, the lake did not recover. In the late 1960s, extensive research was undertaken, resulting in the removal of some 400,000 m^3 of surface sediment (the top meter, in two 50 cm dredgings) from the main basin in 1970 and 1971.

Bengtsson *et al.* (1975) indicated that post-dredging water column concentrations of phosphorus and nitrogen decreased drastically and that the role of the sediment in recycling nutrients was minimized. Phytoplankton diversity increased substantially, while at the same time their productivity was significantly reduced. The size distribution of phytoplankton also shifted to much smaller cells, and water column transparency more than tripled. The troublesome blue- green algal biomass was drastically reduced, with some nuisance species disappearing altogether (Cronberg *et al.* 1975). Conditions in the lake had improved to such a degree by the mid 1970s that an additional research and management program was undertaken on the fish community. From the late 1960s throughout the 1980s, an extensive monitoring program was maintained. By the mid 1980s, this program not only documented a deterioration in water quality, but also the ecological response to the change; and it also helped to ascertain that the changes were due to increased nutrient inputs from the atmosphere and the surrounding drainage basin.

Similar sediment removal projects have been conducted in other areas: Vajgar pond in the Czech Republic, Lake Herman in South Dakota, and Lake Trehorningen in Sweden, just to name a few. The latter named project is of particular note, because although there were significant decreases in the water column concentrations of phosphorus, it remained too high to be algal growth limiting. As a result, algal biomass remained the same as before the dredging was undertaken. This illustrates the importance of having a good understanding and quantification of ecological processes prior to undertaking a remediation project. In addition, Peterson (1982) notes that through the early 1980s there was little evidence to support the effectiveness of sediment removal as a mechanism of ecological remediation. This lack of supporting research and monitoring data continues to be an obstacle to establishing the effectiveness of sediment cleanups.

<u>Metals</u>

Minamata Bay, located in southwestern Japan, is the site of one of the more notorious cases of metal pollution in the environment, and its subsequent impacts on human health. A chemical factory released mercury contaminated effluent into the Bay from 1932 to 1968. In addition to contaminating the water and sediment, methylated mercury accumulated in fish and shellfish. This resulted in toxic central nervous system disease among the individuals who ate these fisheries products over long periods of time. In 1973, the Provisional Standard for Removal of Mercury Contaminated Bottom Sediment was established by the Japanese Environmental Agency. Under this criterion, it was estimated that some 1,500,000 m^3 of sediment would need to be removed from an area of 2,000,000 m^2. Dredging and disposal commenced in 1977 along with an environmental monitoring program to ensure that the activities were not further contaminating the environment. Monitoring included measuring turbidity and other water quality variables, as well as tissue analysis of natural and caged fish for mercury residues. Dredging was completed in 1987, and by 1988 the sampling surveys provided satisfactory evidence that the goals had been achieved. Results of the ongoing monitoring showed that no further deterioration of water quality or increase in fish tissue concentration was occurring. By March of 1990, the confined disposal facility received its final clean cover. The total cost for the project was approximately $40-$42 million U.S. dollars.

Post-project monitoring provided clear evidence of a reduction in surficial sediment concentrations of mercury to a maximum of 8.75 mg/kg and an average concentration of below 5 mg/kg (national criterion is 25 mg/kg) (Ishikawa and Ikegaki 1980; Nakayama *et al.* 1992; Urabe 1993; Hosokawa 1993; Kudo *et al.* 1998). Mercury levels in fish in the bay rose to their maximum between 1978 and 1981, after the primary source had been cut off and some dredging had begun. Tissue concentrations declined slightly as dredging continued; however, they did fluctuate considerably. Fish tissue levels did finally decline below the target levels of 0.4 mg/kg in 1994, some four years after all dredging activity had ceased (Nakayama *et al*. 1996). These results demonstrate that mercury in the sediment continued to contaminate the fish and that removal or elimination of that exposure was essential for ecological recovery to occur. It also demonstrates that some impact (increased availability and increased fish tissue concentrations) could be associated with the dredging activity, and that a significant lag time from the cessation of remediation activity was necessary for the target body burdens to be achieved.

Persistent Toxic Organic Substances

During a 30 year period ending in 1977, at least 1.1 million pounds of PCBs were discharged into the Hudson River, New York, from two General Electric capacitor manufacturing plants located in Fort Edward and Hudson Falls. PCBs contaminated the water, sediment, and biota throughout a 320 km section of the Hudson River. Large-scale surveying and monitoring programs were begun in the mid 1970s to determine the extent of contamination, and to assist in the development and planning of remedial options. Activities including the reduction of PCB levels in the discharge, the dredging for navigational purposes of some 153,000 m^3 of contaminated sediment, and the removal and stabilization of contaminated river bank sediment were conducted between 1977 and 1978.

In 1976, because of the concern over the bioaccumulation of PCBs in fish and other aquatic organisms and their subsequent consumption by people, the State of New York banned fishing in the Upper Hudson River and also banned commercial fishing of striped bass and several other species in the Lower Hudson River. The control of the discharge produced declines in the PCB levels in water, sediment, and fish tissue between 1977 and 1981. Subsequently, PCB levels in fish, which remain the impetus from remediation, have declined at a slower rate, but still persist at levels that cause the continuation of the fish consumption prohibitions and advisories.

U.S. EPA made an interim "no action" decision for the PCB contaminated sediment in 1984. The agency has been conducting a reassessment of its 1984 decision since 1990. In August 1995, the Upper Hudson River was re-opened to fishing, but only on a catch and release basis.

These few examples show that considerable ecological benefits can be obtained from the remediation of contaminated sediment. Surprisingly, the best documented ecological changes are associated with actions relating to nutrient problems, generally in small lakes and ponds and in areas of low human population density, and usually the least costly remediations. Since affiliated research and monitoring has been so lacking, it has been difficult to evaluate the overall success of sediment remediation in a general sense, i.e., to reasonably transfer lessons learned and recommendations on what things are still essential to know, and to achieve cost-effective and essential ecological remediation.

In some cases, even those projects with a great deal of pre-remediation research and monitoring, both unforseen results, as well as disappointing results, were obtained. This reinforces the need to see the approach to sediment remediation as an "adaptive management" phenomenon.

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

V. SEDIMENT REMEDIATION IN THE GREAT LAKES

Contaminated sediment is a major problem in the Great Lakes Basin ecosystem and is well recognized in Remedial Action Plans (RAPs) and Lakewide Management Plans (LaMPs) (SedPAC 1997). Much has been done in contaminated sediment remediation over the last thirteen years and considerable much more will be done in the future. For example, over $580 million has been spent on 38 sediment remediation projects in 19 Areas of Concern over the last thirteen years (Table 2). Not only has substantial resources been spent on sediment remediation, but the rate of increase has accelerated in recent years (Figure 2). In addition, substantially greater resources have been spent on pollution prevention and control as prerequisites to sediment remediation.

Many of these sediment remediation projects (Table 2) were implemented as a result of regulatory actions. In the United States, 31 contaminated sediment remediation projects were implemented as a result of regulatory actions, and one was the result of a public-private partnership. In Canada, 6 contaminated sediment remediation projects have been implemented, 5 by cooperative partnerships and one as a result of industrial action. Of the 38 sediment remediation projects implemented over the last thirteen years, 27 involve dredging and disposal, one involved *in situ* capping, one involved *in situ* treatment, and 9 involve dredging, treatment, and disposal.

Of the sediment remediation projects implemented thus far, only two currently have adequate data and information on ecological effectiveness (i.e., post-project monitoring of beneficial use restoration). These include Waukegan Harbor, Illinois and Black River, Ohio. It should be noted that a number of areas have planned monitoring of ecological effectiveness, but the data will not be available for a number of years. In the cases where sediment remediation was undertaken as a result of regulatory action, these projects were designed to remove a mass of contaminants and reduce environmental risk. These projects were very effective in meeting the regulatory requirements and indeed are consistent with the step-wise and incremental approach to management of contaminated sediment and restoration of beneficial uses called for by the Great Lakes WQB (SedPAC 1997). However, it is recognized that in many cases, much more effort should be placed on forecasting and assessing ecological recovery of an Area of Concern and beneficial use restoration. Again, the purpose of RAPs, as stated in the U.S. - Canada GLWQA, is to restore beneficial uses.

Table 2. A breakdown of sediment remediation projects in Great Lakes Areas of Concern

AREA OF	CONTAMINATED SEDIMENT REMEDIATION PROJECT(S)

CONCERN	
Thunder Bay	• In 1998, approximately 13,000 m^3 of creosote-based contaminated sediment began being removed from the Northern Wood Preservers, Inc. (NWP) site. Contaminated sediment will be dredged, treated, and reused on NWP property. Total project cost is $9.3 million (Canadian), with $3.3 million paid by Environment Canada, $1 million paid by Ministry of Environment, and the remainder paid by Abitibi Consolidation, NWP, and Canadian National Railway Co.
St. Louis River/Bay	• From August-November 1997, Murphy Oil removed approximately 1,800 m^3 of contaminated sediment from the Newton Creek impoundment and 92 m^3 from Newton Creek immediately downstream of the impoundment. Dredged material was solidified with cement and placed in an on-site disposal area, which was then capped. Estimated cost was $250,000.
Manistique River	• In 1998, approximately 23,700 m^3 of PCB contaminated sediment were removed from the harbor. • In 1997, approximately 19,100 m^3 of contaminated sediment were removed from the river and the harbor. • In 1995-1996, about 13,000 m^3 of contaminated sediment near the North Bay were removed. In all three projects, sediment was disposed of in a nearby landfill. The total cost for all three projects to date is $25 million.
Lower Menominee River	• In 1998, U.S. EPA issued a Consent Order requiring remediation of arsenic contamination in the Lower Menominee River. The Consent Order requires Ansul to remove about 7,700 m^3 of arsenic contaminated sediment from the Eighth Street Slip by the end of 1999. Estimated cost is about $1.3 million. • In 1993-1994, approximately 11,500 m^3 of bulk paint sludge were removed by mechanical dredging and transported to a nearby Treatment, Storage, and Disposal facility. This was an emergency removal through administrative orders by the Michigan Department of Environmental Quality (MDEQ). Approximate cost was $50,000.
Milwaukee Estuary	• In 1994, approximately 5,900 m^3 of PCB contaminated sediment were removed from behind Ruck Pond Dam. Over 95% of the mass of PCBs was removed from the system as a result of this project. The total project cost was $7.5 million. • In 1991, approximately 570,000 m^3 of contaminated sediment with varying levels were isolated from the Milwaukee River by the removal of the North Avenue Dam and stabilization of the sediment exposed in the new floodplain with wetland vegetation. The cost involved with the isolation of the contaminated sediment was approximately $1,348,000.
Waukegan Harbor	• As a result of a 1989 Consent Decree, Outboard Marine Corporation provided $20 million for remediation of PCB contaminated sediment. No soils or sediment above 50 mg/kg PCBs remain onsite, except those within containment cells. Approximately 30,000 m^3 of contaminated sediment were dredged in 1992 and placed in two separate containment cells.
Grand Calumet River	• In 1998, the USX Steel Corporation agreed to pay a total of $55 million in a settlement contained in two consent agreements. USX will pay approximately $30 million to remove and dispose of approximately 535,600 m^3 of contaminated sediment from 8.05 km of the lower Grand Calumet River over the next 5 years. USX will also undertake capital improvements estimated at $22 million including wetlands restoration next to the river, construction of a disposal facility for contaminated sediment, and improvement of the Gary facility. • From 1994 to 1996, LTV Steel dredged approximately 89,000 m^3 of contaminated sediment from a slip adjacent to Indiana Harbor. The total project cost was an estimated $14 million.

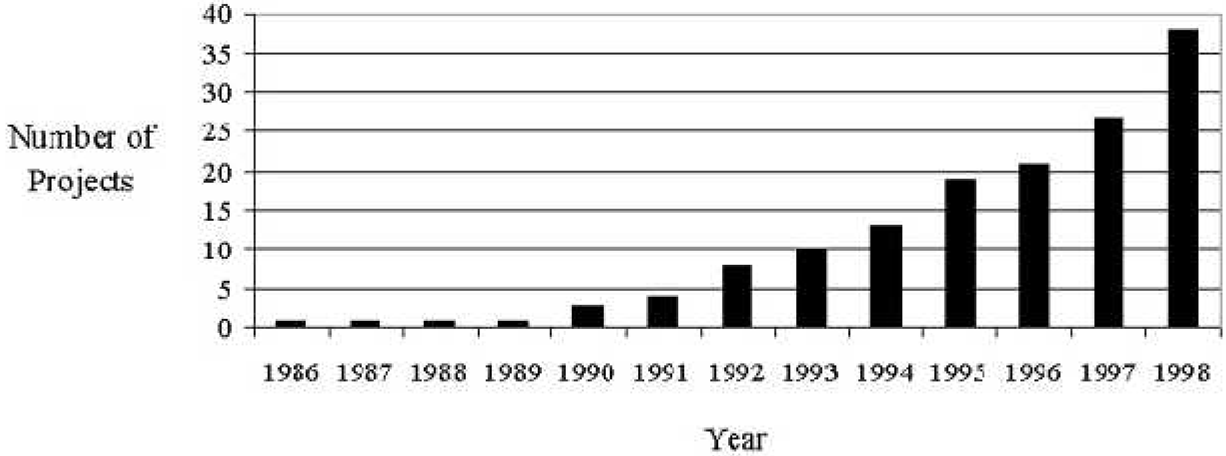
Kalamazoo River	• PAH, mercury, and lead contaminated sediment in Davis Creek was removed from January-April 1999. An estimated 3,100 m^3 of sediment were removed from Davis Creek, and an additional 600 m^3 of hazardous waste from the skimmer pond that outfalls into Davis Creek were also removed. Dredged material was taken off-site for disposal in a landfill. Cost was estimated at $900,000. • In 1998, U.S. EPA ordered the cleanup of the Bryant Mill Pond area of Portage Creek, which is part of the Allied Paper, Inc./Portage Creek/Kalamazoo River Superfund Site. The pond area is no longer under water, but is an exposed floodplain contaminated with PCBs. The cleanup will consist of removal of approximately 68,900 m^3 of PCB contaminants from the creekbed and floodplain areas. Contaminated residuals, sediment, and soil removed will be placed in Bryant lagoon and appropriately covered until a final remedy for on-site containment units is selected by MDEQ. Removal should be completed by the end of 1999. The Potential Responsible Parties are paying U.S. EPA to conduct the removal under a settlement agreement at an estimated cost of $7.5 million.
Saginaw River/Bay	• In 1998, a settlement involving General Motors (GM) Corp., Bay City, and the city of Saginaw was reached that includes $28 million to help restore and protect the Saginaw River and Saginaw Bay. GM will spend $10.9 million on PCB contaminated river sediment dredging. This 1-2 year dredging project is scheduled to begin in 1999, and will remove approximately 264,000 m^3 of contaminated sediment. • A Remedial Investigation/Feasibility Study (RI/FS) conducted from 1986-1997 concluded that there remains significant PCB contamination in the Superfund site of the South Branch of the Shiawassee River. The RI/FS proposes the following: excavation and off-site disposal of soil, river sediment, and floodplain sediment of PCBs > 10 mg/kg in the Cast Forge Plant Area and the South Branch of the Shiawassee River; institutional controls; and limited access. In all, about 35,600 m^3 of sediment will be removed. Cleanup is estimated to begin in about 2 years. The estimated cost for this project is $13,558,000.
Collingwood Harbour	• From 1992 to 1993, approximately 8,000 m^3 of contaminated sediment were removed from the shipyard slips and adjacent areas in the harbour using the Pneuma airlift system. The total project cost, which included partners from Environment Canada Great Lakes Cleanup Fund and the Ministry of Environment and Energy, was an estimated $650,000 (Canadian).
Rouge River	• In 1997-1998, Wayne County removed PCB contaminated sediment from an impoundment (Newburgh Lake) in the Upper Rouge River and placed it in a secure landfill. Approximately 306,000 m^3 of contaminated sediment were removed. The total project cost was an estimated $11 million and funded through U.S. EPA funds from the Rouge River National Wet Weather Demonstration Project. • The PCB source area to Newburgh Lake (Evans Products Ditch Site) was addressed by the MDEQ with support from U.S. EPA. Completed in April 1997, approximately 7,300 m^3 of PCB contaminated stream sediment were removed and transported for disposal at a landfill in Michigan and a hazardous waste disposal facility in New York. The total project cost was approximately $750,000. • In 1986, 30,000 m^3 of zinc contaminated sediment was removed from the Lower Branch of the Rouge River by mechanical dredging and placed in cell #5 of the Corps of Engineers' Pointe Mouille Confined Disposal Facility on southwestern Lake Erie. All dredging and disposal activities were completed at an approximate cost of $1 million.
River Raisin	• Starting in mid July and running through the end of September 1997, Ford Motor Company in Monroe removed approximately 20,000 m^3 of PCB contaminated sediment from a "hot-spot" adjacent to the shipping channel. The PCB contaminated sediment has been

	disposed of in a Toxic Substances Control Act cell that was built on the property of the Ford Monroe Plant. Total cost was approximately $6 million.
Maumee River	• Remediation of an unnamed tributary to the Ottawa River in Toledo, Ohio was completed in June 1998. A total of 6,100 m^3 of sediment, containing 25,300 kg of PCBs, were dredged from the property. This cleanup of PCB contaminated sediment was carried out under a public-private partnership including the City of Toledo, Ohio EPA, U.S. EPA, the U.S. Fish and Wildlife Service, and GenCorp, Inc. The cost of the cleanup was estimated at $5 million. The project was funded by a U.S. EPA grant of $500,000 to Ohio EPA, $140,000 from an Ohio EPA settlement with the City of Toledo, and the remainder from GenCorp. • In 1994, GenCorp remediated the Textileather plant site area. Excavation and disposal of around 4,900 m^3 of contaminated soil occurred. Also as part of the remediation, the storm sewer was power washed and 466,170 L of waste water were collected and treated. Total cost was over $2 million.
Black River	• In 1990, the USS/KOBE Steel Company removed over 38,000 m^3 of PAH contaminated sediment from the Black River mainstem in the areas of the former coke plant outfall. The total project cost, which was funded entirely by USS/KOBE, was $1.5 million.
Ashtabula River	• Plans for future cleanup of contaminated river sediment are now underway. A draft Feasibility Report is scheduled for public release in August 1999 and a Record of Decision in April 2000. Detailed design work is anticipated to begin in Fiscal Year 2000. The construction contract is scheduled to be awarded in April 2002 with project completion by September 2005. The present cost of the comprehensive project is $42,560,000, which includes an estimated $860,000 for ecosystem restoration projects. The project consists of dredging a total of 536,000 m^3 of contaminated river sediment (of which 115,000 m^3 is classified as Toxic Substance Control Act material - PCBs > 50 mg/kg). Dredged material will then be transported to a transfer/dewatering facility and then truck hauled three miles to an upland disposal facility, which will be designed/constructed with two cells to take both non-TSCA and TSCA classified sediment.
Hamilton Harbour	• In 1995, a layer of uncontaminated material was used for *in situ* capping to uniformly cover heavy metals, PCB, and PAH contaminated sediment. The project was funded through the Great Lakes 2000 Cleanup Fund at a cost of $300,000 (Canadian). An additional $350,000 (Canadian) was provided by the National Water Research Institute to further monitor and evaluate the project. • From 1992 to 1994, there was *in situ* treatment of contaminated sediment in one industrial boat slip near the headwall area. Oxygen, iron oxide, and calcium nitrate were injected. This was a demonstration treatment to find the depth of contamination. The total project cost was estimated at $323,000 (Canadian).
St. Clair River	• In 1996, Dow Chemical removed approximately 200 m^3 of pentachlorophenol contaminated sediment. The removal took place about 1 km south of the Cole Drain, about 30 m offshore. The total project cost was estimated at $350,000 (Canadian).
Detroit River	• In 1999, a decision was made to remove a total of 23,000 m^3 of contaminated sediment from the Black Lagoon. A portion of the contaminated sediment will be treated through the "Cement-Lock" process and the remainder will be disposed. Total project cost is approximately $4 million, with dredging costs estimated at $1 million and treatment demonstration costs estimated at $3 million. The project should take about 4 months to complete, and could possibly begin as early as Spring 2000. • Removal of contaminated sediment in Monguagon Creek, a tributary to the Detroit River, was completed in 1997. The project was funded largely by Elf Atochem North America Inc.,

	with an estimated cost of $3 million. Approximately 19,300 m^3 of contaminated sediment were dredged from the creek. • In 1993, Wayne County removed approximately 3,100 m^3 of contaminated sediment near a marina by Elizabeth Park. The total project cost was estimated at $1.33 million.
Niagara River	• In 1996, approximately 21,800 m^3 of contaminated sediment were removed from the 102nd Street Embayment (New York). The entire landfill remediation cost is approximately $30 million. • In 1995, approximately 10,000 m^3 of contaminated sediment were removed from the Welland River (Ontario) using an Amphibex dredge. The total project cost was estimated at $2.6 million (Canadian). • In 1995, approximately 11,500 m^3 of contaminated sediment were removed from Pettit Flume (New York). The approximate cost was $23 million. • In 1992, approximately 6,100 m^3 of contaminated sediment were removed from Gill Creek (New York). The total project cost, which was funded entirely by DuPont, was approximately $10 million. • In 1990, approximately 13,000 m^3 of dioxin contaminated sediment from Black and Bergholtz Creeks (New York) were removed. The total project cost was approximately $14 million.
St. Lawrence River	The New York portion of the AOC involves three major industrial sites. Ongoing remediation projects, as required by New York State and U.S. EPA, address land-based and contaminated river sediment remediation. Some land-based projects involve shoreline and on-site wetland remediation. Projects at each industry include: • **Reynolds Metals** - The shoreline remediation requires contaminated river sediment removal, with completion expected by the end of 2000. Total volume removed will be approximately 59,370 m^3. The contaminated river sediment work is estimated to cost $62.4 million. The land-based plant site remediation, which includes wetlands remediation, is nearing completion at a cost of $53.7 million. • **General Motors** - During the summer of 1995, GM completed the major portion of its St. Lawrence dredging with the removal of approximately 11,500 m^3 of PCB contaminated river sediment. The river work to date has cost $10 million. The extent of required treatment and disposal for the dredged materials is under review. Further river sediment remediation in a cove adjacent to the St. Regis Mohawk Tribe remains to be completed. Total project costs, including land-based actions with groundwater recovery and treatment, are estimated to cost $78 million. • **ALCOA** - The major "hot-spot" at the plant outfall in the Grasse River was remediated in 1995 as part of a "non-time critical removal action." This involved the removal of approximately 3,000 m^3 of PCB contaminated river sediment. The results of this project are under review as is the feasibility of other remedial alternatives downstream from the outfall in the Grasse River up to the St. Lawrence River confluence. Major land-based inactive hazardous waste site remediation at the ALCOA plant site continues with 10 of the 14 Record of Decision sites now completed. Overall remediation costs are estimated to be in excess of $250 million.

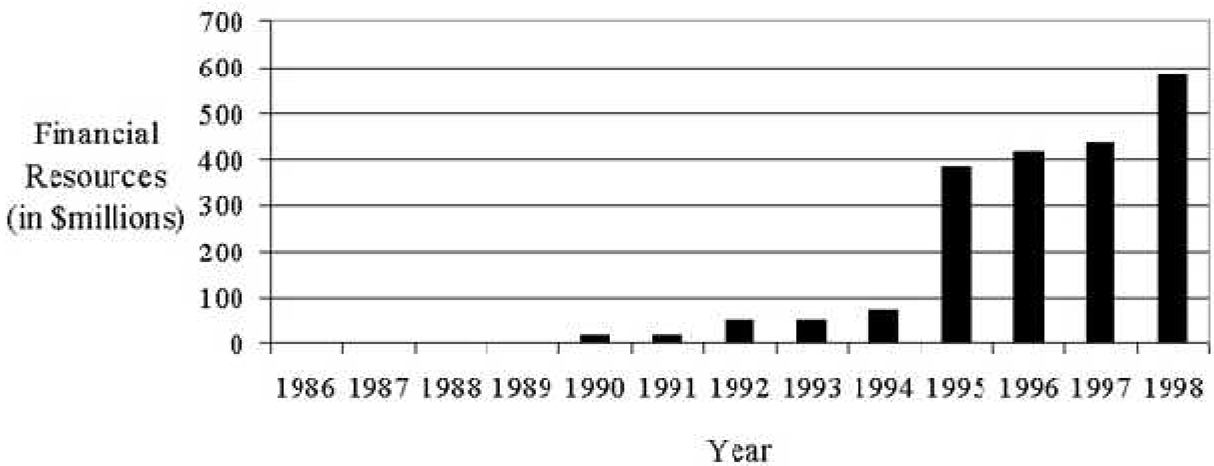
Figure 2. Trends in sediment remediation in Great Lakes Areas of Concern: A. Cumulative number of sediment remediation projects; B. Cumulative financial resources expended on sediment remediation; and C. Cumulative volume of sediment removed

A.



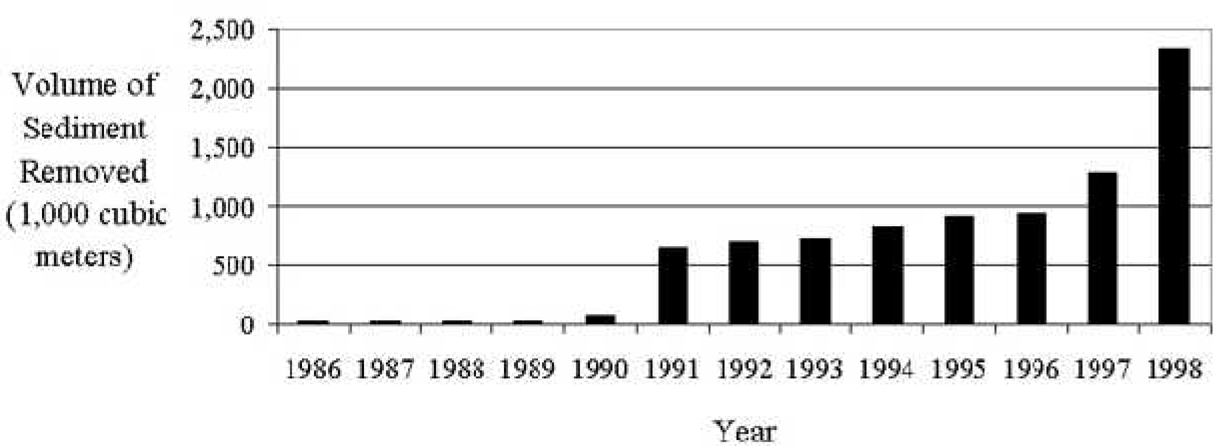
Number of Projects
40
35
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
Year

B.



Financial Resources (in $millions)
700
600
500
400
300
200
100
0
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
Year

C.



Volume of Sediment Removed (1,000 cubic meters)
2,500
2,000
1,500
1,000
500
0
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
Year

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

VI. CASE STUDIES OF SEDIMENT REMEDIATION AND ASSOCIATED ECOLOGICAL BENEFITS

PCB Contaminated Sediment Remediation in Waukegan Harbor

Waukegan Harbor is situated in Lake County, Illinois on the western shore of Lake Michigan. Constructed by filling a natural inlet and portions of adjacent wetlands, Waukegan Harbor has water depths varying from 4.0 to 6.5 m. The harbor sediment is composed of soft organic silt (muck) which lies over medium, dense, fine-to-coarse sand.

In 1990, approximately 75 commercial ship dockings were present in the harbor. The majority of the materials brought through the harbor were building/construction materials for nearby Chicago industries (Hey and Associates 1993).

Although substantial recreational use occurs in the area around the harbor, land use in the Waukegan Harbor area is primarily industrial. Of the major facilities present, the Outboard Marine Corporation (OMC) was identified as the primary source of PCB contamination in harbor sediment. In 1972, OMC dismantled a coke oven gas plant (previously built and owned by the North Shore Coke and Chemical Company) to construct their own facilities for manufacturing recreational marine products. U.S. EPA investigations in 1976 revealed high levels of PCBs in Waukegan Harbor sediment and in soil close to OMC outfalls. Concurrently, high levels of PCBs (above the U.S. Food and Drug Administration action levels of 2.0 mg/kg PCB) were also found in resident fish species. As a result, in 1981, the U.S. EPA formally recommended that no fish from Waukegan Harbor be consumed. Subsequently, the Lake County Health Department posted signs warning residents that consumption of fish from the northern harbor could be dangerous to human health.

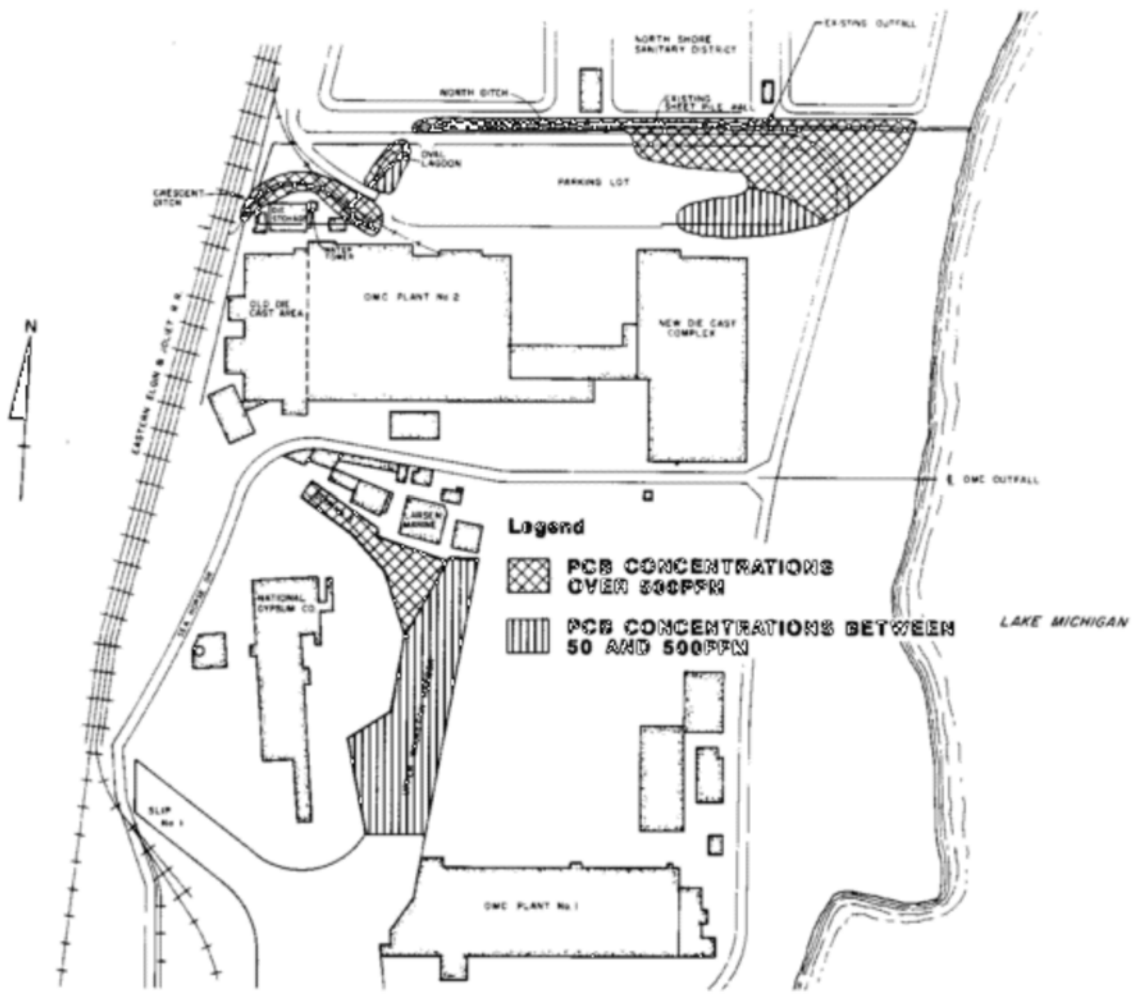
With the discovery of Waukegan Harbor's PCB problem in 1976, the U.S. EPA and Illinois EPA became involved in a lengthy litigation process with OMC, and as a result of the requirements of the 1980 Comprehensive Environmental Response Compensation and Liability Act (Superfund) and its 1986 Amendments, a Consent Decree was entered by the U.S. Justice Department in District Court in 1989. The Consent Decree called for remediation of the contaminated sediment greater than 50 mg/kg PCBs.

Early investigations of harbor sediment indicated that approximately 136,000 kg of PCBs were in the harbor proper (International Joint Commission 1989). In the most highly contaminated areas of the harbor (Slip #3), PCB concentrations in sediment were as high as 500,000 mg/kg (Figure 3). Severely contaminated areas totaled about 19 ha, including the Upper Harbor, Slip #3, and land on the northern edge of OMCs property

(International Joint Commission 1987a).

Remedial efforts in the harbor began in 1990, with harbor dredging conducted in 1992. As a result of the Consent Decree, OMC provided approximately $20-25 million for remediation, which included the construction of three containment cells. Approximately 24,500 m^3 of PCB contaminated sediment was removed from the harbor using a hydraulic dredge. Approximately 2,000 m^3 of PCB contaminated sediment in excess of 500 mg/kg PCBs was removed from Slip #3 (a "hot spot" that accounts for the majority of the PCBs on the site), and thermally extracted onsite to at least 97% (Taciuk Process). Soils in excess of 10,000 mg/kg of PCBs were also excavated

Figure 3. Outboard Marine Corporation site before remedial action (U.S. EPA 1988)



and treated onsite by thermal extraction (Hartig and Zarull 1991). In all, 11,521,400 kg of material were treated, and 132,500 liters of PCBs were extracted and taken offsite for destruction. The treated harbor sediment was placed in the OMC containment cells. The upper harbor sediment that was dredged was placed in the Slip #3 containment cell. Extracted PCBs were transported to an offsite facility for high-temperature combustion (>2200^{o}F) in accordance with the U.S. Toxic Substances Control Act (TSCA). No soils or sediment that exceeded 50 mg/kg PCBs remained onsite, except those within the containment cells.

Following completion of the soil and sediment remediation, the cells were closed and capped with a high density polyurethane liner and a soil cover. Extraction wells in each cell maintain an inward hydraulic gradient, to prevent PCB migration. The cells are operated and maintained by OMC. To offset the loss of slip

#3, a new slip (#4) was dredged and opened to the public in July 1991.

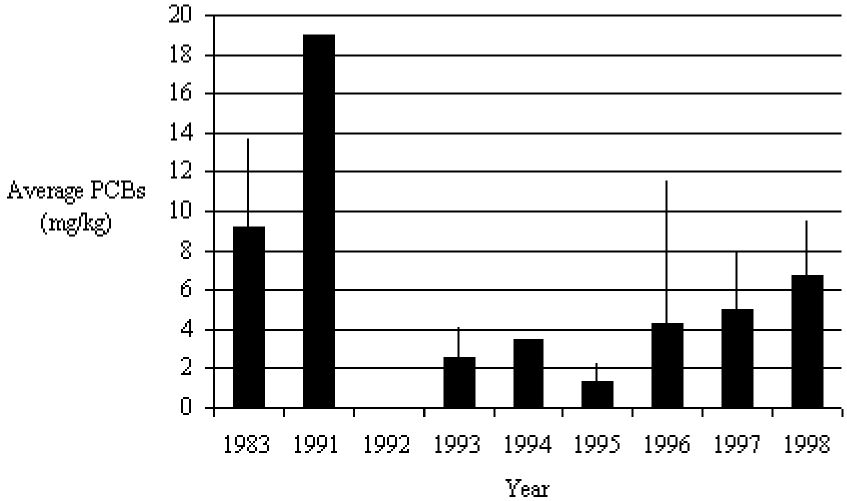
OMC was required to comply with the 1989 Consent Decree and all Superfund requirements. In addition, extracted PCBs had to be transported and incinerated in accordance with requirements of the U.S. TSCA. The primary cleanup target was the removal, containment, and treatment of contaminated sediment in and around the OMC property in order to meet the 50 mg/kg PCB limit determined under the consent decree.

Fish contaminant monitoring, conducted after the Superfund remediation dredging in 1992, shows a substantial decrease for PCB concentrations in carp fillets. Figure 4 presents trend data for PCBs in Waukegan Harbor carp fillets (Illinois Environmental Protection Agency undated memo; Illinois Environmental Protection Agency 1996; U.S. Environmental Protection Agency - STORET). PCB levels in 1993 fish suggest that dredging did not cause significant PCB resuspension. Contaminant levels in 1993 fish averaged 5 fold lower than those tested in previous years up through 1991 (Table 3). Contaminant levels from 1993-1995 appeared to remain at these lower levels, but there is a suggestion of an apparent increase for the period 1996-1998. There is no statistically significant difference between the 1983 and 1998 levels of PCBs in carp (based on a two sample t-test using the data in Table 3).

As a result of the dramatic decline of PCBs in several fish species between the late 1970s and 1990s, the posted Waukegan Harbor fish advisories were removed, although fish advisories still exist for carp and other fish throughout Lake Michigan. The Illinois Lake Michigan Lakewide Advisory is protective of human health, as PCB concentrations in Waukegan Harbor fish are considered similar to those found elsewhere in Lake Michigan.

Approximately 136,000 kg of PCBs were removed from the sediment through this Superfund action. Sediment sampling indicates that about 900 kg of PCB contaminated sediment remains in the navigational channel of the harbor. This PCB contamination and silting has resulted in cargo carrier restrictions on ships passing into the channel. The Department of Transportation has observed disturbance of navigational sediment by prop wash. The U.S. Army Corps of Engineers, working with the Waukegan Port District, is in the second phase of a study to dredge the remaining contaminated sediment from Waukegan Harbor. The proposed project has three objectives: to remove the remaining contaminated material that lies outside of the Federal navigational channel (an estimated 23,000 m^3); to deepen the inner and outer harbor to a proposed 7-8.2 m and 7.6-8.8 m depth, respectively; and to complete maintenance dredging (207,000 m^3) of the Federal navigational channel (the Superfund cleanup occurred in the uppermost portion of the inner harbor, which lies outside of the Federal navigational channel; the navigational channel itself hasn't been dredged since the early 1970s). The total amount of sediment to be dredged in this project is 230,000 m^3, at a total estimated cost of $12-14 million. Work could possibly begin in 2002, with the first year involving construction of a Confined Disposal Facility and the second year consisting of dredging.

Figure 4. Average PCB levels, with 95% confidence intervals, in Waukegan Harbor carp fillets



(1991 and 1994 - one sample only; 1992 - dredging occurred, no sampling)

Table 3. Qualitative comparison of PCB levels in Waukegan Harbor fish

Year	Species	PCBs (mg/kg)	Description of Sample	Reference or Source
1978	carp	26.5	whole	U.S. EPA
	alewife	1.8	whole	U.S. EPA
	white sucker	3.6	whole	U.S. EPA
1979	carp	38.5	whole	U.S. EPA
	carp	18.4	whole	U.S. EPA
	carp	8.2	whole	U.S. EPA
	alewife	1.8	whole	U.S. EPA
	white sucker	26.8	whole	U.S. EPA
1981	alewife	3.8	whole	U.S. EPA
	alewife	1.6	whole	U.S. EPA
1983	carp	6.5	fillet	U.S. EPA
	carp	9.0	fillet	U.S. EPA
	carp	12.0	fillet	U.S. EPA
1991	carp	19.0	fillet	Illinois EPA
	alewife	10.0	whole	Illinois EPA
1992	alewife	0.17	whole	Illinois EPA
1993	carp	2.66	fillet	Illinois EPA
	carp	2.4	fillet	Illinois EPA
	carp	6.39	fillet	Illinois EPA
	carp	1.84	fillet	Illinois EPA
	carp	1.60	fillet	Illinois EPA
	carp	0.60	fillet	Illinois EPA

	alewife	0.10	whole	Illinois EPA
	alewife	0.17	whole	Illinois EPA
	white sucker	1.06	whole	Illinois EPA
	white sucker	0.62	whole	Illinois EPA
	white sucker	0.10	whole	Illinois EPA
	white sucker	0.01	whole	Illinois EPA
1994	carp	3.45	fillet	Illinois EPA
	white sucker	1.17	whole	Illinois EPA
1995	carp	1.3	whole	Illinois EPA
	carp	1.71	fillet	Illinois EPA
	carp	1.29	fillet	Illinois EPA
1995	carp	0.99	fillet	Illinois EPA
	alewife	0.05	whole	Illinois EPA
	alewife	0.24	whole	Illinois EPA
	alewife	0.44	whole	Illinois EPA
	alewife	0.10	whole	Illinois EPA
	white sucker	0.26	whole	Illinois EPA
	white sucker	0.37	whole	Illinois EPA
	white sucker	0.52	whole	Illinois EPA
1996	carp	4.4	fillet	Illinois EPA
	carp	8.00	fillet	Illinois EPA
	carp	0.10	fillet	Illinois EPA
	alewife	0.4	whole	Illinois EPA
	alewife	0.39	whole	Illinois EPA
	white sucker	0.17	fillet	Illinois EPA
	white sucker	0.36	fillet	Illinois EPA
	white sucker	0.86	whole	Illinois EPA
	white sucker	0.77	whole	Illinois EPA
	white sucker	0.90	whole	Illinois EPA
	white sucker	0.30	whole	Illinois EPA
1997	carp	1.7	fillet	Illinois EPA
	carp	2.8	fillet	Illinois EPA
	carp	3.7	fillet	Illinois EPA
	carp	7.8	fillet	Illinois EPA
	carp	9.2	fillet	Illinois EPA
1998	carp	8.1	fillet	Illinois EPA
1998	carp	7.3	fillet	Illinois EPA
	carp	4.9	fillet	Illinois EPA

PAH Contaminated Sediment Remediation in the Main Stem, Black River

The Black River enters the south shore of Lake Erie at Lorain Harbor, in north-central Ohio between Cleveland and Sandusky. This river system drains approximately 1,210 km^2 of Lorain, Medina, Ashland, Huron, and Cuyahoga Counties. The geographic limits of the Area of Concern are considered to be the entire river basin.

The Black River drainage basin is dominated by agricultural and rural land uses (89%). Residential, commercial, and recreational uses make up the remaining 11%, and are concentrated in the lower regions of the river. Although USS/KOBE Steel Company is the primary industry in the lower river (between river kilometer 8.7 and 3.3), several other major facilities are located further upstream.

The Area of Concern has 45 National Pollutant Discharge Elimination System (NPDES) permitted dischargers - 26 industrial and 19 municipal. Of the industrial dischargers, the only one that is considered to be "major" (discharging >1 million gallons/day) by the U.S. EPA is USS/KOBE Steel. Until 1982, USS operated a coking facility, which is considered to have been the major source of PAH and metal contamination within the area.

A 1985 Consent Decree (U.S. District Court - Northern District of Ohio 1985) mandated USS/KOBE Steel Company to remove 38,000 m^3 of PAH contaminated sediment from the mainstem of the Black River. The goal of the sediment remediation project was to remove PAH contaminated sediment in order to eliminate liver tumors in resident brown bullhead populations.

Tests from 1980 confirmed the presence of elevated levels of cadmium, copper, lead, zinc, cyanide, phenols, PAHs, oils, and grease in sediment adjacent to the former USS steel coke plant outfall. PAH concentrations in this area totaled 1,096 mg/kg (Baumann *et al.* 1982). Tests also confirmed the presence of low levels of pesticides (DDT and its metabolites) in both the mainstem and the harbor regions (Black River Remedial Action Plan Coordinating Committee 1994). This sediment exceeded U.S. EPA's Heavily Polluted Classification for Great Lakes harbor sediment. As a result, all mainstem and harbor sediment dredged during U.S. Army Corps of Engineers maintenance operations required disposal in a confined disposal facility.

High sediment PAH levels corresponded to a high frequency of liver tumors in resident populations of brown bullheads (Black River RAP Coordinating Committee 1994). Although sediment PAH levels had declined since the USS's coking facility was shut down, levels were still of concern.

Sediment remediation occurred upstream of the federal navigational channel in the vicinity of the coke plant outfall. Dredging of the sediment began in 1989. The operation utilized a closed, watertight, clamshell dredge to reduce the loss of sediment to the water column. To prevent the spread of oil, an oil boom was erected. The sediment was moved from a dredge barge to a containment cell on the USS/KOBE site using specially designed vehicles. Although the sediment was not considered hazardous waste, the disposal site had special design requirements to clean all hazardous waste from the cell, line it, allow for dewatering of the dredged sediment and collection of the decanted water for treatment, capping after the dredged materials were deposited, and post-closure monitoring. Without these conditions, the placement of the dredged sediment in the cell would have exacerbated existing ground water contamination and violated Resource Conservation and Recovery Action (RCRA) requirements for closure. In the event of a spill, a contingency plan was defined and environmental monitoring was conducted prior to, during, and following dredging. A total of 38,000 m^3 of sediment were removed during the operation. This action was completed in December 1990.

Under the Consent Decree, USS/KOBE Steel paid $1.5 million for the dredging and containment of the sediment. USS/KOBE Steel was required to comply with the 1985 Consent Decree (U.S. District Court - Northern District of Ohio 1985). The Consent Decree was issued to deal with violations of the Clean Air Act, but included several supplementary environmental requirements, one of which was the dredging of the PAH contaminated sediment. In addition, disposal of dredged sediment had to comply with U.S. RCRA requirements. The dredging project also required permits under the Clean Water Act for NPDES, Section 404 dredge and fill, and a Section 401 water quality certification.

The primary cleanup target was the removal of sediment in the area of the former USS coke plant to "hard bottom", or the underlaying shale bedrock. No quantitative environmental targets or endpoints were established, although post-dredging sampling was required to test for remaining areas of elevated PAH concentrations.

Prior to dredging, PAH concentrations ranged from 8.8-52.0 mg/kg within Black River sediment. As a result of dredging, PAH concentrations in sediment declined (Table 4).

Table 4. PAH concentrations (mg/kg) in Black River sediment in 1980 (during coke plant operations), 1984 (coking facility closed, pre-dredging), and 1992 (post-dredging)

PAH compound	1980[a]	1984[b]	1992[c]
Phenanthrene	390.0	52.0	2.6
Fluoranthrene	220.0	33.0	3.7
Benzo(a)anthracene	51.0	11.0	1.6
Benzo(a)pyrene	43.0	8.8	1.7

(USS coking facility closed down in 1982, dredging occurred from 1989-1990)

[a]Baumann *et. al.* (1982)

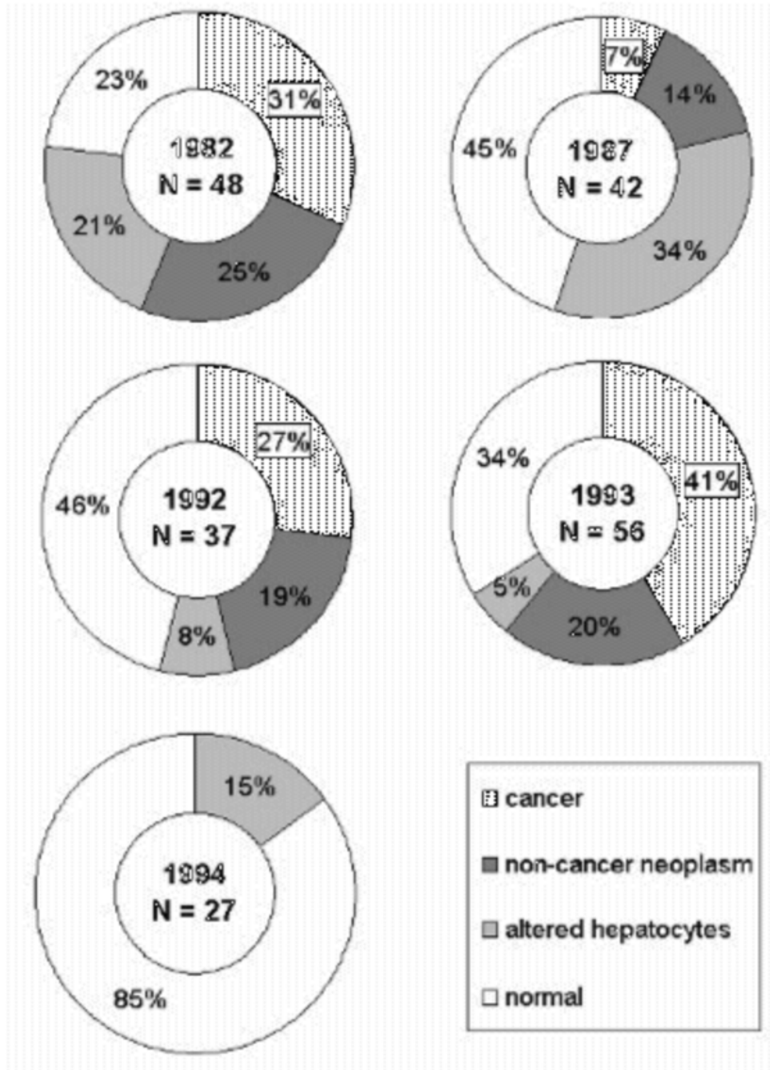
[b]Fabacher *et. al.* (1988)

[c]Black River Remedial Action Plan Coordinating Committee (1994)

PAH levels in brown bullheads, which had been monitored since the early 1980s (Baumann *et al.* 1982; Baumann and Harshbarger 1995), suggest some very interesting relationships between liver neoplasms and the dredging of sediment. Figure 5 illustrates the prevalence of hepatic tissue conditions (cancer, non-cancer neoplasm, altered hepatocytes, normal) found in fish of age 3 in 1982 (during coke plant operations), 1987 (after coke plant closing, prior to dredging), 1992 (exposed to dredging as age 1), 1993 (exposed to dredging as young of year), and 1994 (hatching after dredging was completed).

The incidence of liver cancer in bullheads of age 3 decreased between 1982 and 1987, corresponding with decreased PAH loadings following the coke plant closure in 1982. There is general consensus that the increase in liver cancer found in the 1992 and 1993 surveys is a result of PAH redistribution which occurred during the 1990 dredging efforts. No instance of liver cancer was found in 1994 samples of age 3 brown bullheads. Further, the percent of normal liver tissues increased from 34% to 85% between 1993 and 1994. This elimination of liver tumors and the increase in the percentage of normal tissues in the resident brown bullhead populations as a result of sediment remediation provides substantial evidence of the efficacy of the remedial strategy.

Figure 5. Percentage of age 3 brown bullheads from the Black River having various liver lesions (Baumann and Harshbarger [in press])



Existing Links Between Contaminated Sediment and Ecological Damage

Establishing quantitatively the ecological significance of sediment-associated contamination in any area is a difficult time- and resource-consuming exercise. It is, however, absolutely essential that it be done. It will likely be used as the justification to force action, and also as the rationale for proposing when intervention is necessary in one place but not another. Bounding the degree of ecological impact (at least semi-quantitatively) provides for realistic expectations for improvement if sediment remediation is pursued. It should also provide essential information on linkages that could be used in other use restoration components in the RAP (e.g., habitat improvements to increase population levels, etc.).

Based on the investigations, a rather straightforward ranking of sites should be possible. At best, a ranking among Areas of Concern, but at worst, a ranking of sites within an individual Area of Concern. However, in order to do this, and thereby establish a priority for action, the investigation should also provide information of a temporal nature (that is, how stable are the observed relationships with time, what are the key controlling factors, and what temporal scales are they expressed or affected on?). This information is critical, whether a non-intervention or an intervention option for remediation is chosen. In the former case, while the sediment-associated contaminant may not be responsible for any significant ecological damage, conditions may change in the future (e.g., sewage loads increase, leading to increased oxygen demand in the water and sediment, leading to changes in the redox conditions at the sediment-water interface, leading to increased bioavailability of a metal, leading to toxic effects, leading to population shifts in the benthos, and so on). In the latter case, attention may be focused on one specific contaminant or condition, while others are ignored because they are of little or no immediate significance. When conditions are changed because of a cleanup, surprise and disappointment may result (e.g., anoxic bottom waters resulting from high organic sediment oxygen demand are removed, invertebrate and demersal fish species once absent due to anoxia now inhabit the area and are exposed to low-level concentrations of a persistent organic compound that biomagnifies, leading to reproductive problems in fish-eating birds). In establishing the present and potential linkages among sediment-associated contaminants and the biota, some information regarding physical stability is essential to complete the temporal picture. Knowledge of susceptibility to resuspension and dispersion of contaminant deposits may affect their priority ranking for cleanup.

Some selected examples of Areas of Concern in the Great Lakes that have compiled and interpreted some of the critical information necessary to link sediment-associated contaminants and specific ecological damage or impairment are presented here. In some cases, they are only a first step in what needs to eventually be done, and they may not yet be quantitative enough to establish and evaluate all of the relationships and conditions described above; however, the value of the information and the effort that has gone into it should be recognized and shared. These are areas where little or no sediment remediation has taken place; however, some of the difficult groundwork essential for the development and implementation of a sediment remedial action plan has.

The Natural Resource Damage Assessments performed in Green Bay (Lake Michigan) and Saginaw Bay (Lake Huron) are good examples of where this link has been made. In Green Bay, contaminated sediment has been quantitatively linked to both fish consumption advisories and reproductive impairment of the Forster's tern population. In Saginaw Bay, contaminated sediment has been linked to fish consumption advisories and reproductive impairment of the common tern population. The linkage of contaminated sediment to use impairments in Saginaw Bay resulted in a $28 million settlement, $10.9 million of which was allocated for PCB contaminated sediment remediation (Table 2).

The Bay of Quinte, Lake Ontario, is nutrient enriched to the point of impairment. Historical inputs of nutrients, especially phosphorus, resulted in excessive algal growth, nuisance algal blooms, and widespread and excessive growth by aquatic macrophytes. These conditions, in turn, have been responsible for (or partially responsible for) taste and odor problems in the drinking water, reduced oxygen in the bottom waters, shifts in the plankton and fish communities, and navigational and recreational problems. The record of increasing nutrient enrichment has been codified in the sediment of the bay. Ironically, it is the sediment that "...will delay the further recovery of the ecosystem and it does affect our ability to influence the ecosystem and improve water quality" (Bay of Quinte Remedial Action Plan Coordinating Committee and Bay of Quinte Remedial Action Plan Public Advisory Committee 1989). Considerable research and monitoring on the external loadings of nutrients, the internal loading (sediment recycling), and ecological processes has quantified the relative significance of the sediment and provided the Bay of Quinte RAP with the information necessary to plan their remediation of these problems.

Hamilton Harbour, Lake Ontario, is contaminated with nutrients, oxygen demanding substances, metals, and persistent organics. All of these contaminants can be found in the harbour sediment in high concentrations. In an attempt to remediate the sediment-associated problems, the RAP Technical Team developed an approach, which was endorsed by the RAP Stakeholders (Canada Ontario Agreement 1985):

> *The strategy has three essential components. First, it notes that successful remediation depends on source control, as a first priority. It includes, among sources to be controlled, zones of sediment in which concentrations of contaminants are very high. It specifies the locations of these zones, and recommends active intervention in these locations through a combination of removal and in situ treatment. Second, the strategy includes experimentation with techniques such as capping, which may or may not be appropriate as a remedial measure or a follow-up to remedial measures. Third, the strategy calls for monitoring and research to evaluate progress, and to see whether once the above measures have been taken, a passive approach will yield the desired result over time.*

The basis for the active intervention part of this strategy stems from detailed studies of the sediment contaminants and their effects on biota (toxicity testing and benthic invertebrate community structure). The second and third parts of the strategy recognize the importance of research and adaptive management to solving a complex problem.

In a number of Canadian Areas of Concern, such as Collingwood Harbour, Spanish River, Severn Sound, and the St. Lawrence River (Cornwall area), a new sediment assessment technique has been applied. This technique, based on biological guidelines, links contaminated sediment with biological effects, allows these effects to be quantified, and allows intercomparisons and priority setting among Areas of Concern and sites within Areas of Concern. These guidelines incorporate the structure of benthic invertebrate communities by using predictive models that relate physical/chemical habitat to an expected community structure and functional responses such as growth, reproduction, and survival in four toxicity tests (bioassays) with benthic invertebrates, using ten test endpoints. Research has established guidelines that allow determination of the community as unstressed, potentially stressed, stressed, or severely stressed. In addition, sediment can be classified as either non-toxic, potentially toxic, or toxic. To simplify the assessment process, software has been developed that incorporates the complex analyses required by the approach and provides the user with straightforward categories of sediment quality on a site by site basis. Where this technique has been applied, an increased understanding of the role, significance, and mode of expression of contaminated sediment has been acquired. In addition, the technique has consistently demonstrated that the volumes of sediment requiring intervention are significantly smaller than were initially estimated, based on chemical guidelines (Reynoldson and Day 1994; Reynoldson *et al*. 1995; Reynoldson 1998; Reynoldson and Day 1998).

Future sediment remediation will undoubtedly be contingent upon relating ambient contamination with beneficial use restoration. In particular, it will be essential to establish the relationship between contaminated sediment remediation and ecological improvement or benefit. Accomplishing this requires not only an understanding of the linkages involved, but also a quantification of those relationships. This will not only drive remediation, but also frame expectation.

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

VII. CONCLUSIONS AND RECOMMENDATIONS

All 42 Areas of Concern in the Great Lakes Basin have contaminated sediment based on the application of chemical guidelines. In addition, there is a consensus among government, industry, non-governmental organizations, and RAP groups that contaminated sediment is a major cause of environmental problems, as well as a key factor in restoring 11 of the 14 beneficial use impairments identified in the GLWQA.

In most Areas of Concern, the documentation of the sediment problem has not been quantitatively coupled to the ecological beneficial use impairments. Therefore, stipulating how much needs to be cleaned up, why, and what improvements can be expected to the beneficial use impairment(s) over time has not been possible. A clear understanding of these relationships and some level of quantification is critical for the development of a complete sediment management strategy. This understanding should provide adequate justification for an active cleanup program, and also represents a principle consideration in the adoption of non-intervention alternative strategies. In developing this understanding, it is important not only to know the existing degree of ecological impairment associated with sediment contaminants, but also the circumstances under which those relationships and impacts might change (i.e., contaminants become more available or more detrimental).

Over the past thirteen years, over $580 million has been spent on 38 remediation projects in 19 Areas of Concern. Of these sediment remediation projects, only two currently have adequate data and information on ecological effectiveness (i.e., post-project monitoring of beneficial use restoration). In some cases there is planned monitoring of ecological effectiveness, but the data will not be available for a number of years. In the cases where sediment remediation was undertaken as a result of regulatory action, the projects were designed to remove a mass of contaminants in order to reduce environmental risk. These projects were very effective in meeting the regulatory requirements, and indeed are consistent with the step-wise and incremental approach to management of contaminated sediment called for by the Great Lakes WQB (SedPAC 1997). However, it is recognized that in many cases, much more effort should be placed on forecasting and assessing ecological recovery of an Area of Concern, as well as beneficial use restoration consistent with Annex 2 of the GLWQA. Therefore, SedPAC recommends:

- **that much greater emphasis be placed on post-project monitoring of effectiveness of sediment remediation (i.e., assessment of effectiveness relative to restoration of uses, with appropriate quality assurance/quality control).**

One way of achieving this would be for the State/Provincial/Federal agency staff responsible for sediment remediation to incorporate into settlements and cooperative agreements some specific commitments and resources required for post-project monitoring of effectiveness of sediment remediation. Good examples of this include the Welland River project (Ontario), the settlement under the Natural Resource Damage Assessment for Saginaw River and Bay (Michigan), and the Thunder Bay cleanup project (Ontario).

Globally, the best documented ecological changes following sediment remediation are associated with actions relating to nutrient problems, generally in small lakes and ponds and in areas of low human population density, and generally the least costly remediations. Since affiliated research and monitoring has been so lacking, it has been difficult to evaluate the overall success of sediment remediation, in a general sense (i.e., to reasonably transfer lessons learned and recommendations on what things are still essential to know, and to achieve cost-effective and essential ecological remediation).

It is also recognized that ecological benefits of sediment remediation may not be seen because of the magnitude of the contaminated sediment problem in the area and in remaining downstream areas of contamination, which would mask or delay ecological recovery (e.g., see Grand Calumet River/Indiana Harbor Ship Canal and Milwaukee Estuary in Table 2). Areas of Concern where the probability of measuring ecological benefits of sediment remediation is high include: Manistique River, Michigan; Collingwood Harbour, Ontario; River Raisin, Michigan; Newburgh Lake Impoundment on the Rouge River, Michigan; and the unnamed tributary to the Ottawa River, Ohio. SedPAC recommends:

- **a high priority be placed on monitoring ecological benefits and beneficial use restoration at these sites.**

Although a basic understanding of aquatic ecosystem function and chemical fate is generally available, aquatic ecosystems appear to be sufficiently unique and our understanding sufficiently lacking. Therefore, an adaptive management approach is the prudent course to follow. This approach requires a much tighter coupling of research, monitoring, and management in every case to develop quantifiable, realistic goals and measures of success to achieve them.

Clearly, there are knowledge gaps in our understanding of the relationships between contaminated sediment and the 11 use impairments from the GLWQA that are potentially affected by contaminated sediment. Therefore, SedPAC recommends that:

- **additional research is essential to: quantify the relationships between contaminated sediment and known use impairments, forecast ecological benefits, and monitor ecological recovery and beneficial use restoration in a scientifically defensible and cost effective fashion.**

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

VIII. LITERATURE CITED

Adams, W. J., Kimerle, R. A. and R. G. Mosher. 1983. *Aquatic Safety Assessments of Chemicals Sorbed to Sediments*. Proceedings of the Seventh Annual Aquatic Toxicology Symposium, Arpil 17-19, 1983. Milwaukee, Wisconsin.

Allan, R. J. 1986. *The Role of Particulate Matter in the Fate of Contaminants in Aquatic Ecosystems.* IWD Scientific Series No. 142. Burlington, Ontario. 128 pp.

Augenfield, J. M. and J. W. Anderson. 1982. "The Fate of Polyaromatic Hydrocarbons in an Intertidal Sediment Exposure System: Bioavailability to *Macoma inquinata (Mollusa: Pelecyopoda)* and *Abarenicola pacifica (Annelida: Polychaeta)*." Mar. Envrion. Res. 7:31-50.

Baumann, P. C. and J. C. Harshbarger. 1995. "Decline in Liver Neoplasms in Wild Brown Bullhead Catfish After Coking Plant Closes and Environmental PAHs Plummet." Environmental Health Perspectives. 103(2):168-170.

Baumann, P. C., Smith, W. D. and M. Ribick. 1982. "Hepatic Tumor Rates and Polynuclear Aromatic Hydrocarbon Levels in Two Populations of Brown Bullhead (*Ictalurus nebulosus*)." *Polynuclear Aromatic Hydrocarbons. Sixth International Symposium on Physical and Biological Chemistry.* eds. Cook, M. W., A. J. Dennis and G. L. Fisher. BaTelle Press: Columbus, Ohio. pp. 93-102.

Baumann, P. C. and J. C. Harshbarger. [in press]. *Liver Neoplasm Trends in Black River Bullhead.* 18 pp.

Bay of Quinte Remedial Action Plan Coordinating Committee and Bay of Quinte Remedial Action Plan Public Advisory Committee (BOQ). 1989. *Bay of Quinte Remedial Action Plan "Time To Decide" - A Discussion Paper*. Canada-Ontario. Toronto, Ontario. 90 pp.

Bengtsson, L., Fleischer, G., Lindmark, G. and W. Ripl. 1975. "Lake Trummen Restoration Project I. Water and Sediment Chemistry." Vert. Int. Verein. Limnol. 19:1080 -1087.

Bishop, C. A., Mahony, N. A., Trudeau, S. and K. E. Pettit. 1999. "Reproductive Success and Biochemical Effects in Tree Swallows (*Tachycineta Bicolor*) Exposed to Chlorinated Hydrocarbon Contaminants in Wetlands of the Great Lakes and St. Lawrence River Basin, USA and Canada." Env. Toxicol. Chem. 18:263-271.

Bishop, C. A., Ng, P., Pettit, K. E., Kennedy, S. W., Stegeman, J. J., Norstrom, R. J. and R. J. Brooks. 1998. "Environmental Contamination and Development Abnormalities in Eggs and Hatchlings of the Common Snapping Turtle (*Chelydra serpentina serpentina*) From the Great Lakes-St. Lawrence River Basin (1989-91)." Environmental Pollution. 101: 143-156.

Bishop, C. A., Koster, M. D., Chek, A. A., Hussell, D. J. T. and K. Jock. 1995. "Chlorinated Hydrocarbons and Mercury in Sediments, Red-Winged Blackbirds (*Agelaius Phoneniceus*), and Tree Swallows (*Tachycineta Bicolor*) From Wetlands in the Great Lakes-St. Lawrence River Basin." Environ. Toxicol. Chem. 14:491-501.

Bishop, C. A., Brooks, R. J., Carey, J. H., Ng, P., Norstrom, R. J. and D. R. S. Lean. 1991. "The Case for a Cause-Effect Linkage Between Environmental Contamination and Development in Eggs of the Common Snapping Turtle (*Dhelydra S. Serpentina*) from Ontario, Canada." J. Toxicol. Environ. Health. 33:521-547.

Black River Remedial Action Plan Coordinating Committee. 1994. *Black River Remedial Action Plan Stage One Report: Impairment of Beneficial Uses and Sources of Pollution in the Black River Area of Concern*. Ohio Environmental Protection Agency and the Black River Coordinating Committee, 9880 South Murray Ridge Road, Elyria, Ohio.

Bonin, J., DesGranges, J. L., Bishop, C. A., Rodrigue, J. and A. Gendron. 1995. "Comparative Study of Contaminants in the Mudpuppy (*Amphibia*) and the Common Snapping Turtle (*Reptilia*), St. Lawrence River, Canada." Arch. Environ. Contam. Toxicol. 28:184-194.

Canada Ontario Agreement (COA). 1985. *Contaminated Sediment in Hamilton Harbour: An Update to the Remedial Action Plan Stage 2 Report*. Hamilton, Ontario. 15 pp.

Chapman, P. M. and R. Fink. 1984. "Effects of Puget Sound Sediments and Their Elutriates on the Life Cycle of *Capitella capita*." Bull. Environ. Contam. Toxicol. 33:451-459.

Cronberg, G., Gelin, C. and K. Larsson. 1975. "Lake Trummen Restoration Project II. Bacteria, Phytoplankton and Phytoplankton Productivity." Verh. Int. Verein. Limnol. 19:1088-1096.

Durham, R. W. and B. G. Oliver. 1983. "History of Lake Ontario Contamination from the Niagara River by Radiodating and Chlorinated Hydrocarbon Analysis." J. Great Lakes Res. 9:160-168.

Environment Canada and U.S. Environmental Protection Agency. 1997. *State of the Great Lakes*. Burlington, Ontario. 76 pp.

Environment Canada and U.S. Environmental Protection Agency. 1995. *State of the Great Lakes*. Burlington, Ontario. 56 pp.

Fabacher, D. L., Schmitt, C. J., Besser, J. M. and M. J. Mac. 1988. "Chemical Characterization and Mutagenic Properties of Polycyclic Aromatic Compounds in Sediment from Tributaries of the Great Lakes." Environmental Toxicology and Chemistry. 7:529-543.

Forstner, U. and G. T. W. Whittman. 1979. *Metal Pollution in the Aquatic Environment*. Springer-Verlag, Berlin.

Gannon, J. E. and A. M. Beeton. 1971. "Procedures for Determining the Effects of Dredged Sediments on Biota - Benthos Viability and Sediment Selectivity Tests." J. Water Pollut. Control Fed. 43:392-398.

Gendron, A. D., Bishop, C. A., Fortin, R. and A. Hontela. 1997. "*In Vitro* Testing of the Functional Integrity of the Corticosterone-Producing Axis in MudPuppy (*Amphibia*) Exposed to Chlorinated Hydrocarbons in the Wild." Environ. Toxicol. Chem. 16:1694-1706.

Harder, H. W., Carter, T. V. and T. F. Bidleman. 1983. "Acute Effects of Toxaphene and Its Sediment-Degraded Products on Estuarine Fish." Can. J. Fish. Aquat. Sci. 40:2119-2125.

Harding, L. W. and J. H. Phillips. 1978. "Polychlorinated Biphenyls: Transfer From Microparticulates to Marine Phytoplankton and the Effects on Photosynthesis." Science. 202:1189-1192.

Hartig, J. H. and M. A. Zarull. 1991. "Methods of Restoring Degraded Areas in the Great Lakes." Reviews of Environmental Contamination and Toxicology. 117:127-154.

Hey and Associates. 1993. *Waukegan Remedial Action Plan - Stage 1 Final Report*. Libertyville, Illinois. 106 pp. + appendices.

Hoke, R. A. and B. L. Prater. 1980. "Relationship of Percent Mortality of Four Species of Aquatic Biota From 96-Hour Sediment Bioassays of Five Lake Michigan Harbors and Elutriate Chemistry of the Sediments." Bull. Envrion. Contam. Toxicol. 25:394-399.

Hosokawa, Y. 1993. "Remediation Work for Mercury Contaminated Bay - Experiences of Minamata Bay Project, Japan." Wat. Sci. Tech. 28:339-348.

Illinois Environmental Protection Agency. 1996 memo. Lake Michigan Fish Contaminant Data Summary 1991-1995. Illinois EPA's Bureau of Water.

International Joint Commission (IJC). 1989. *Progress in Developing and Implementing Remedial Action Plans for Areas of Concern in the Great Lakes Basin - Appendix A.* Great Lakes Water Quality Board. Windsor, Ontario. 196 pp.

International Joint Commission (IJC). 1987a. *Report on Great Lakes Water Quality*. Great Lakes Water Quality Board. Windsor, Ontario. 236 pp.

International Joint Commission (IJC). 1987b. *Progress in Developing Remedial Action Plans for Areas of Concern in the Great Lakes Basin - Appendix A.* Great Lakes Water Quality Board. Windsor, Ontario. pp 73-78.

International Joint Commission (IJC). 1982. *Guidelines and Register for Evaluation of Great Lakes Dredging Projects*. Dredging Subcommittee. Windsor, Ontario. 365 pp.

Ishikawa, T. and Y. Ikegaki. 1980. "Control of Mercury Pollution in Japan and the Minamata Bay Cleanup." Journal WPCF. 52:1013-1018.

Kemp, A. L. W. and R. L. Thomas. 1976. "Cultural Impact on the Geochemistry of the Sediments of Lake Ontario, Erie, and Huron." GeoSci. Can. 3:191-207.

Krezovich, J. P., Harrison, F. L. and R. G. Wilhelm. 1987. "The Bioavailability of Sediment-Sorbed Organic Chemicals: A Review." Water, Air, and Soil Pollution. 32:233-245.

Kudo, A., Fujikawa, Y., Miyahara, S., Zheng, J., Takigami, H., Sugahara, M. and T. Muramatsu. 1998. "Lessons From Minamata Mercury Pollution, Japan - Afer a continuous 22 Years of Observation." Wat. Sci. Tech. 38:187-193.

Larsen, D. P., Malueg, K. W., Schults, D. and R. M. Brice. 1975. "Response of Eutrophic Shagawa Lake, Minnesota, U.S.A., to Point-Source, Phosphorus Reduction." Verh. Internat. Verein. Limnol. 19:884-892.

Leger, C. 1989. *Cleaning up Great Lakes Areas of Concern: How Much Will It Cost?* Northeast-Midwest

Institute: Washington, D.C. 45 pp.

Lower, W. R., Yanders, A. F., Marrero, T .R., Underbring, A. G., Drobner, V. K. and M. D. Collins. 1985. "Mutagenicity of Bottom Sediment From a Water Reservoir." Environ. Toxicol. Chem. 4:13-19.

Malins, D. C., McCain, B. B., Brown, D. W., Varanasi, U., Krahn, M. M., Myers, M. S. and S. L. Chan. 1984. "Sediment-Associated Contaminants and Liver Diseases in Bottom-Dwelling Fish." Hydrobiologia. 149:67-74.

Malueg, K. W., Schuytema, G. S., Gakstatter, J. H. and D. F. Krawczyk. 1983. "Effect of *Hexagenia* on *Daphnia* Responses in Sediment Toxicity Tests." Environ. Toxicol. Chem. 2:73-82.

Michigan Department of Natural Resources (MDNR). 1988. *Remedial Action Plan for Saginaw River and Saginaw Bay Area of Concern.* Michigan Department of Natural Resources, Surface Water Quality Division. Great Lakes and Environmental Assessment Section. Lansing, Michigan. 588 pp.

Milbrink, G. 1983. "Characteristic Deformities in Tubificid Oligochaetes Inhabiting Polluted Bays of Lake Vanern, Southern Sweden." Hydrobiologia. 106:169-184.

Mohlenberg, F. and T. Kiorboe. 1983. "Burrowing and Avoidance Behaviour in Marine Organisms Exposed to Pesticide-Contaminated Sediment." Mar. Pollut. Bull. 14:57-60.

Nakayama, Y., Nakai, O., Nanba, T. and K. Kyuuma. 1996. "Effect of the Minamata Bay Environment Restoration Project." Unpublished Contribution. Proceedings 17th US/Japan Experts Meeting: Management of Bottom Sediments Containing Toxic Substances, 12-14 March, 1996, Oakland, CA.

Nakayama, Y., Kyumau, K., Hirota, R. and M. Fujiki. 1992. *Treatment of Bottom Sediment Containing Mercury and Monitoring Method Using Fishes. Proceedings of the 13th U.S./Japan Experts Meeting: Management of Bottom Sediments Containing Toxic Substances, 3-5 November, 1987*. Baltimore, MD. T. R. Patin (ed). U.S. Army Corps of Engineers, Water Resources Support Center. pp.1-22.

National Academy of Sciences (NAS). 1983. *Risk Assessment in the Federal Government: Managing the Process.* National Academy Press: Washington, D.C.

Nau-Ritter, G. M. and C. F. Wurster. 1983. "Sorption of Polychlorinated Biphenyls (PCBs) To Clay Particulates and Effects of Desorption on Phytoplankton." Water Res. 17:383-387.

Nriagu, J. O. 1986. "Metal Pollution in the Great Lakes in Relation to Their Carrying Capacity." *The Role of the Oceans as a Waste Disposal Option*. Ed. G. Kullenberg. Reidel Publ.: Dordrecht, The Netherlands. pp. 441-468.

Nriagu, J. O., Kem, A. L. W., Wong, H. K. T. and N. Harper. 1979. "Sedimentary Record of Heavy Metal Pollution in Lake Erie." Geochem. Cosmo. Acta. 43:247-258.

Persaud, D., Jaagumagi, R. and A. Hayton. 1992. *Guidelines for the Protection and Management of Aquatic Sediment Quality in Ontario*. Ontario Ministry of the Environment. Toronto, Ontario. 23 pp.

Peterson, S. A. 1982. "Lake Restoration by Sediment Removal." Water Res. Bull. 18:423-435.

Powers, C. D., Nau-Ritter, G. M., Rowland, R. G. and C. F. Wurster. 1982. "Field and Laboratory Studies of the Toxicity to Phytoplankton of Polychlorinated Biphenyl (PCBs) Desorbed From Fine Clays and Natural Suspended Particulates." J. Great Lakes Res. 8: 350-357.

Prater, B. L. and M. A. Anderson. 1977a. "A 96-Hour Bioassay of Otter Creek, Ohio." J. Water Pollut.

Control. Fed. 49:2099-22106.

Prater, B. L. and M. A. Anderson. 1977b. "A 96-Hour Sediment Bioassay of Duluth and Superior Harbor Basins (Minnesota) Using *Hexagenia limbata, Asellus communis, Daphnia magna,* and *Pimephales promelas* as Test Organisms." Bull. Environ. Contam. Toxicol. 18:159-169.

Reichert, W. L., Le Eberhart, B. T. and U. Varanasi. 1985. "Exposure of Two Species of Deposit-Feeding Amphipods to Sediment-Associated [^{3}H] benzo[a]pyrene: Uptake, Metabolism, and Covalent Binding to Tissue Macromolecules." Aquati. Toxicol. 3:45-56.

Reynoldson, T.B. 1998. *An Assessment of Sediment Quality and Benthic Invertebrate Community Structure in the St. Lawrence (Cornwall) Area of concern.* NWRI Report No. 98-233. 20 pp.

Reynoldson, T. B. and K. E. Day. 1998. *Biological Guidelines for the Assessment of Sediment Quality in the Laurentian Great Lakes.* NWRI Report No. 98-232. 119 pp.

Reynoldson, T. B., Rosa, F., Mudroch, A. and K. E. Day. 1995. *Investigation of the Spanish River Area of the North Channel of Lake Huron. II. Benthic Invertebrate community Structure and Sediment Toxicity; With Reference to Biological Sediment Guidelines.* NWRI Report No. 95-14. 44 pp.

Reynoldson, T. B. and K. E. Day. 1994. *An Assessment of Sediment Quality and Benthic Invertebrate Community Structure in Collingwood Harbour. An Area of Concern: Towards Delisting.* NWRI Publication No. 94-42. 46 pp.

Reynoldson, T. B., Mudroch, A. and C. J. Edwards. 1988. *An Overview of Contaminated Sediments in the Great Lakes With Special Reference to the International Workshop held at Aberystwyth, Wales, U.K.* International Joint Commission. Windsor, Ontario. 41 pp.

Robbins, J. A., Mudroch, A. and B. G. Oliver. 1990. "Transport and Storage of ^{137}Cs and ^{210}Pb in Sediments of Lake St. Clair." Can. J. Fish. Aquat. Sci. 47:572-587.

Roesijadi, G, Anderson, J. W. and J. W. Blaylock. 1978a. "Uptake of Hydrocarbons from Marine Sediments Contaminated With Prudhoe Bay Crude Oil: Influence of Feeding Type of Test Species and Availability of Polycyclic Aromatic Hydrocarbons." J. Fish. Res. Bd. Can. 35:608-614.

Roesijadi, G., Woodruff, D. L. and J. W. Anderson. 1978b. "Bioavailability of Napthalenes From Marine Sediments Artifically Contaminated With Prudhoe Bay Crude Oil." Environ. Pollut. 15:223-229.

Salamons, W. and U. Forstner. 1984. *Metals in the Hydrocycle*. Springer-Verlag, Berlin.

Sediment Priority Action Committee (SedPAC). 1997. *Overcoming Obstacles to Sediment Remediation in the Great Lakes Basin.* International Joint Commission. Windsor, Ontario. 22 pp + Appendices.

Sutter, G. W, II. 1997. "Overview of the Ecological Risk Assessment Fremework." *Ecological Risk Assessments of Contaminated Sediments*. Eds. C. G. Ingersoll, T. Dillon and G. R. Biddinger. SETAC Press: Pensacola, Florida. 389 pp.

Tagatz, M. E., Plaia, G. R. and C. H. Deans. 1985. "Effects of 1,2,4-trichlorobenzeneon Estuarine Macrobenthic communities Exposed via Water and Sediment." Ecotoxicol. Environ. Safety. 10:351-360.

Thomas, R. L. and R. Frank. 1987. "Introduction." Hydrobiologia. 149:1-4.

Thomas, R. L. and A. Mudroch. 1979. *Small Craft Harbours - Sediment Survey Lakes Ontario, Erie and St.*

Clair. Report to Small Craft Harbours, Ontario Region, Department of Fisheries and Oceans Canada. Burlington, Ontario.

Urabe, S. 1993. "Outline of Mercury Sediment Work in Minamata Bay." Unpublished Proceedings of the 16th U.S./Japan Experts Meeting: Management of Bottom Sediments Containing Toxic Substances, 12-14 October, 1993. Kitukyushu, Japan.

U.S. Army Corps - Waterways Experiment Station (WES). 1984. *Potential for Biomagnification of Contaminants Within Marine and Freshwater Food Webs.* Technical Report D-84-7, Department of the Army. Vicksburg, Mississippi. 166 pp.

U.S. District Court - Northern District of Ohio. 1985. Consent Decree with USS/KOBE Steel.

U.S. Environmental Protection Agency. 1999. *Agenda for Action.* Region V, Chicago, Illinois.

U.S. Environmental Protection Agency. 1998a. *Agenda for Action.* Region V, Chicago, Illinois.

U.S. Environmental Protection Agency. 1998b. *EPA's Contaminated Sediment Management Strategy.* US EPA Office of Water, Washington, D.C. EPA-823-R-98-001. 105 pp.

U.S. Environmental Protection Agency. 1997. *Agenda for Action*. Region V, Chicago, Illinois.

U.S. Environmental Protection Agency. 1992. *Framework for Ecological Risk Assessment.* Washington, D.C. EPA/630/R-92/001.

U.S. Environmental Protection Agency. 1989. *Risk Assessment Guidance for Superfund. Volume 1. Human Health Evaluation Manual. Part A. Interim Final*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. Washington, D.C. EPA/540/1-89/002.

U.S. Environmental Protection Agency. 1988. *Cleanup of Outboard Marine Corporation/Waukegan Harbor Site*. Office of Public Affairs. Chicago, Illinois. 8 pp.

Wardlaw, C., Brendon, D. and W. Randle. 1995. "Results of Canada's Contaminated Sediment Treatment Technology Program." *Sediment Remediation '95.* Workshop Proceedings, Windsor, Ontario. May 8-10, 1995. 18 pp.

Warwick, W. F. 1980. "Paleolimnology of the Bay of Quinte, Lake Ontario 2800 Years of Cultural Influence." Can. Bull Fish. Aquat. Sci. 206:1-117.

West, W. R., Smith, P. A., Booth, G. M. and M. L. Lee. 1986. "Determination and Genotoxicity of Nitrogen Heterocycles in a Sediment From the Black River." Environ. Toxicol. Chem. 5:511-519.

Wiederholm, T. 1984. "Incidence of Deformed Chironomid Larvae (*Diptera: Chironomidae*) in Swedish Lakes." Hydrobiologia. 109:243-249.

Zarull, M. A. and A. Mudroch. 1993. "Remediation of Contaminated Sediments in the Laurentian Great Lakes." Reviews of Environmental Contamination and Toxicology. 132:93-115.

ECOLOGICAL BENEFITS OF CONTAMINATED SEDIMENT REMEDIATION IN THE GREAT LAKES BASIN

Prepared by: Michael A. Zarull, John H. Hartig, and Lisa Maynard
Sediment Priority Action Committee
Great Lakes Water Quality Board

August, 1999

IX. APPENDIX A - SEDIMENT PRIORITY ACTION COMMITTEE MEMBERSHIP

- Carol Ancheta, Environment Canada
- Jim Bredin, Michigan Department of Environmental Quality
- Murray Brooksbank, Environment Canada
- Kelly Burch, Pennsylvania Department of Environmental Protection
- Dave Cowgill, United States Environmental Protection Agency
- Judy Crane, Minnesota Pollution Control Agency
- Don Dewees, University of Toronto
- Bonnie Eleder, United States Environmental Protection Agency
- Frank Estabrooks, New York Department of Environmental Conservation
- John Hartig, International Joint Commission
- Greg Hill, Wisconsin Department of Natural Resources
- Gail Krantzberg, Ministry of Environment
- Julie Letterhos, Ohio Environmental Protection Agency
- Lisa Maynard, International Joint Commission
- Jan Miller, United States Corps of Engineers
- Mahesh Podar, United States Environmental Protection Agency
- Karl Schaefer, Canada Centre for Inland Waters
- Griff Sherbin, Environment Canada
- Michael Zarull, Canada Centre for Inland Waters